ENERGY FOR A SUSTAINABLE WORLD

José Goldemberg
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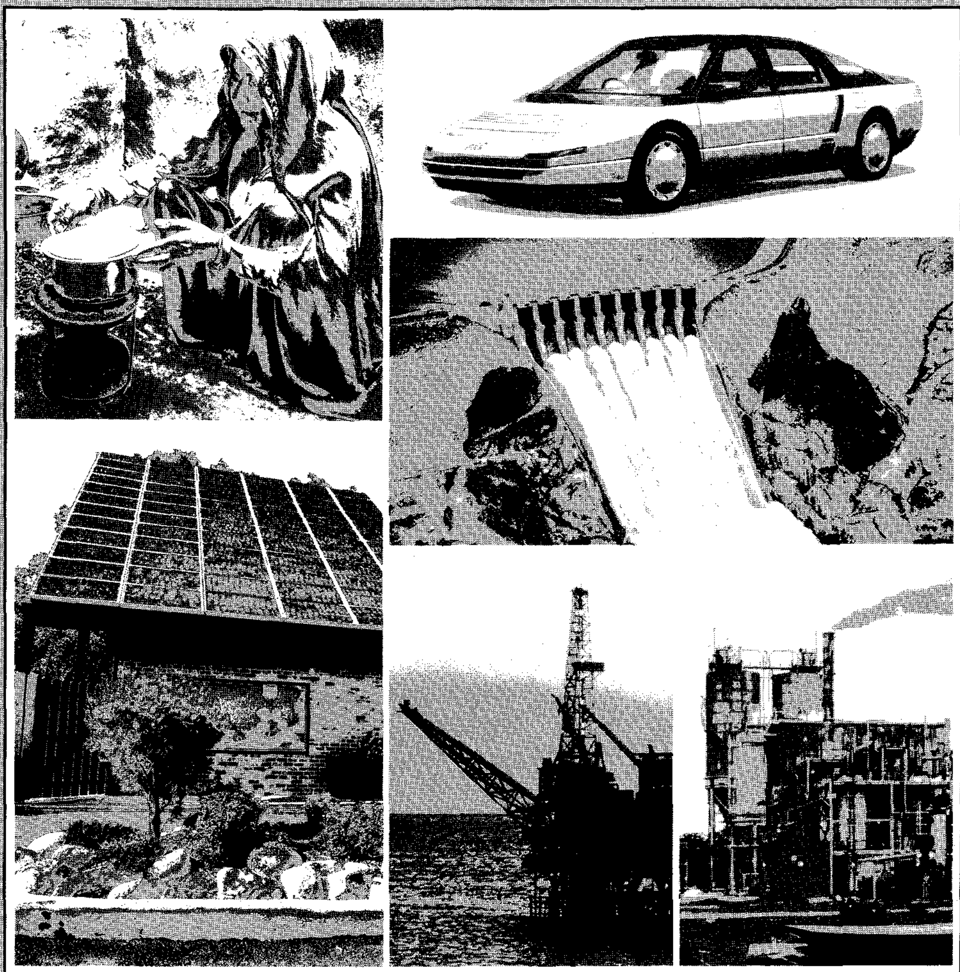
Amulya K.N. Reddy
Robert H. Williams



WORLD RESOURCES INSTITUTE

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Acknowledgments

This report presents the major global findings of the End-Use Global Energy Project (EUGEP), of which the authors are co-organizers. Results of this project are presented in more detail in a book of the same title being published by Wiley-Eastern, New Delhi, India.

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Foreword

The 1970s saw nothing less than a revolution in energy use in the industrialized countries. While energy demand had grown in lockstep with economic growth for decades, the oil price shocks of 1973–74 and 1978–9 shattered that historical relationship. So profound was the change that between 1973 and 1986 there was no growth in U.S. energy use while the economy grew by 30 percent. Comparable declines in the energy intensity of the economy occurred in Western Europe and Japan.

This change confounded much conventional energy analysis, and has fostered a new breed of energy analysts who have been studying the energy problem, not with a primary focus on supply, but with detailed analysis of energy demand. Whereas conventional energy analysts posed the question: "What mix of energy supplies can best meet projected demand?" (with demand based on projected macroeconomic trends), this new breed asked instead: "What actual uses is energy needed for and how can those needs be most efficiently met?" Foremost among these "end-use" analysts have been the authors of this study, an international team of José Goldemberg (Brazil), Thomas B. Johansson (Sweden), Amulya K. N. Reddy (India), and Robert H. Williams (U.S.), with whom WRI has collaborated for several years.

What the EUGEP (End Use Global Energy Project) analysts have found, and actual experience has demonstrated, is that it is possible to get far more bang for the energy buck than anyone dreamed possible before 1973, and far more than conventional energy analysis still suggests today. How much more is, in essence, the subject of this study.

Building on detailed studies of the energy economies of the United States, Sweden, India, and Brazil, the EUGEP global energy scenario for 2020 suggests a per capita energy use in the industrialized countries of about half what it was in 1980 (3.2 kilowatts per person rather than 6.3 kilowatts). Envisioning a widespread shift in the developing world from traditional, inefficiently used non-commercial fuels to modern energy technologies used in high efficiency applications, the EUGEP scenario sees an average of 1.3 kilowatts per capita (contrasted to the present average of 1.0 kilowatts) supporting a living standard up to that of Western Europe today. Overall, even with population rising to 7 billion, the EUGEP scenario portrays a world in which global energy use is only 10 percent higher than it is today, a stark contrast to conventional projections which show an increase of more than 100 percent.

The EUGEP analysis is neither a projection nor a policy prescription. It is rather an illustration (a rather conservative one in that it employs only commercially available or near-commercial technologies) of what is technically possible. Nonetheless, its policy implications are profound. Foremost among these is the far greater flexibility and freedom of maneuver governments have if they must plan for a 10 percent rather than a 100 percent increment in energy supply. Instead of having to push on nearly every energy front to meet projected demand, the EUGEP message to policymakers is that they can choose.

The EUGEP scenario described in detail in these pages embodies choices that reflect the authors' particular values: limited growth in the use of nuclear power so as to lower nuclear proliferation risks; a balanced energy supply mix to reduce oil imports from the Middle East and thereby promote national self-reliance and enhanced global security; and, limits in the use of coal in particular and fossil fuels in general so as to diminish the extent of greenhouse warming and other environmental risks.

To my mind these are good choices. Individual policymakers may differ in their priorities. What remains crucial in this work is the demonstration that at or near the present level of global energy use, plausible energy supply mixes can be identified that would not seriously aggravate other pressing global environmental and security problems, as conventional energy strategies do.

The work carried out by the authors of this study is closely tied to the research conducted at WRI since 1983. WRI has studied the role of bioenergy in development and industry, staged an international conference on the same theme and investigated the impacts of energy subsidies in promoting inefficient energy use in both industrialized and developing countries. WRI's scientific and policy work on the greenhouse effect, on the depletion of the earth's ozone shield, and on acid rain, tropospheric ozone, and other air pollutants, also ties in directly with the recommendations of this study on how to satisfy economic goals without running up against severe environmental constraints.

WRI is pleased to have worked closely with the EUGEP authors in supporting their work and in making the results of their research available. Their effort is an excellent example of collaborative research at the international level on an issue of global importance.

Both WRI and the EUGEP group wish to express their gratitude to the following organizations which generously provided the financial support that made this study possible: the Rockefeller Brothers Fund, the John D. and Catherine T. MacArthur Foundation, the Alida and Mark Dayton Charitable Trust, the Energy Research Commission of Sweden, the International Labor Organization, the Max and Anna Levinson Foundation, the Swedish International Development Authority, and the Macauley and Helen Dow Whiting Foundation.

James Gustave Speth
President
World Resources Institute

The Energy Crisis Revisited

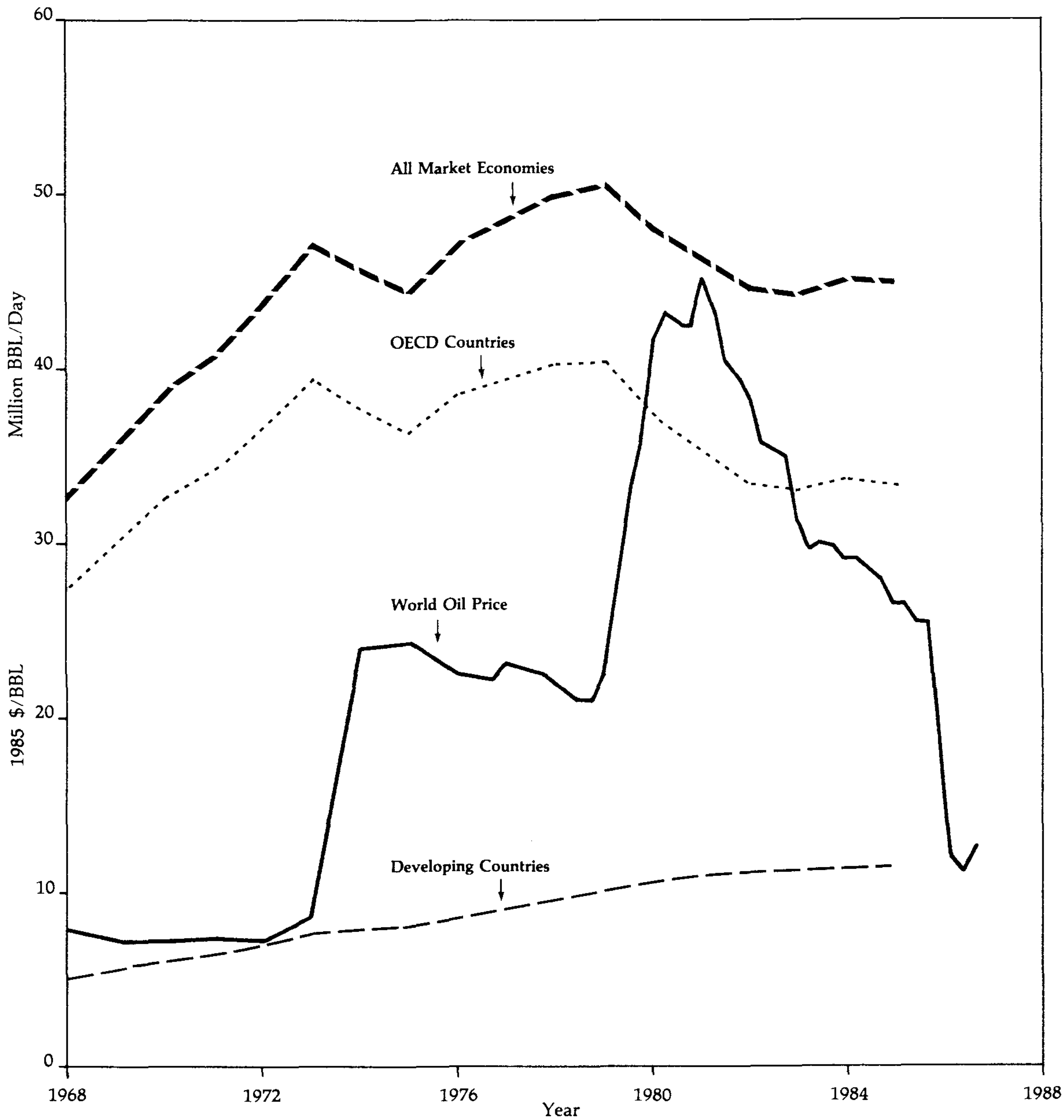
The sharp rises in world oil prices in 1973 and 1979 shook the world economy to its foundations. *(See Figure 1.)* Between 1973 and 1981 the industrialized world paid $1.5 trillion (1984 dollars) more for oil imports than it would have paid had the world oil price remained at the 1972 level. Although oil exporters recycled some of this money back to the industrialized market economies through increased investments and purchases, the price rises resulted in a tremendous transfer of wealth and a huge loss in purchasing power that has affected all goods and services. Increased oil cost is certainly one of the main causes of the stagflation—simultaneous economic stagnation and price inflation—that beset those economies in the 1970s.

Poor countries also suffered. By 1981, low- and medium-income developing countries were spending, respectively, 61 and 37 percent of their export earnings on oil imports.[1] *(See Table 1.)* These countries use their export earnings to purchase technologies for industrial and agricultural development and to pay international debts. The cost of imported oil became a financial drain on the developing world, economic growth in many poor countries stalled, and a debt repayment crisis occurred.

The sharp increases in world oil prices also contributed to real price increases for other energy forms, such as natural gas. Rises in electricity prices, though, have been due largely to other factors. Between 1979 and 1985, while oil prices were falling sharply, the average price of electricity increased 21 percent in Japan, 20 percent in the United States, and 12 percent in Western Europe. Electricity prices rose because of the high cost of additional generating capacity. In other words, the marginal cost of electricity is high compared to the current average price. In the United States, the problem dates back to the early 1970s, when the long-term downward trend in electricity prices reversed itself. *(See Figure 2.)* The cost of electricity generated by coal and nuclear power rose sharply in the 1970s, largely because of quality control problems and more restrictive environmental and safety regulations.

The capital costs of energy supplies are generally rising. In the United States, from 1972 to 1982 capital expenditures for energy supplies increased from 26 to 39 percent of all new plant and equipment expenditures (from 2.5 to 4 percent of gross national product) while domestic production remained constant.[2] In developing countries, the share of domestic investments committed to expanding energy supplies increased from 1 to 2 percent of gross domestic product in 1970 to 2 to 3 percent in 1980. Foreign exchange requirements for energy investments in developing countries totaled about $25 billion in 1982, or approximately one third of the foreign exchange required for all investments.[3]

Figure 1. The World Oil Price and Oil Consumption Rates



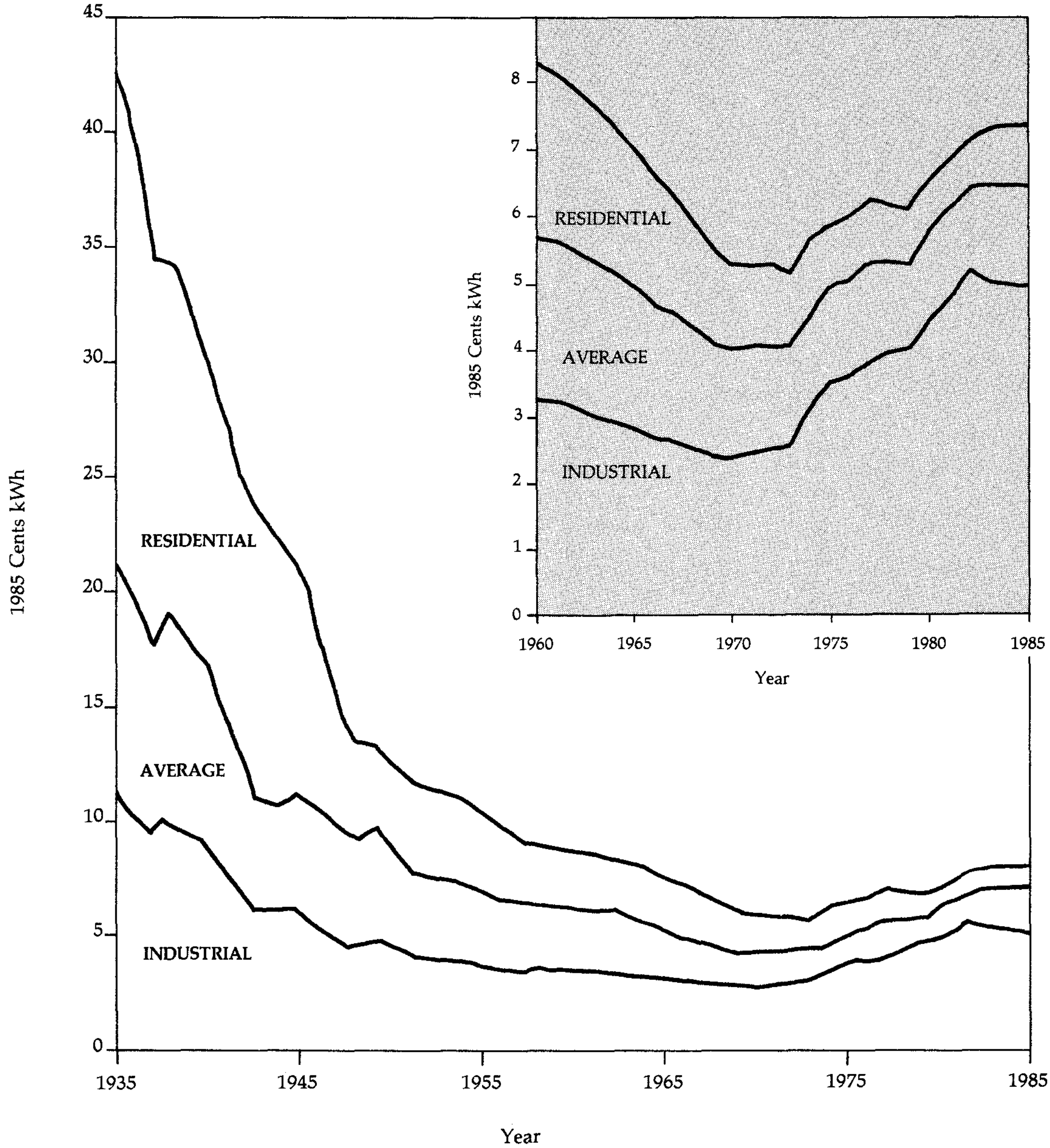
The rate of oil consumption (in million barrels per day) is shown separately for the member countries of the Organisation for Economic Co-operation and Development, for developing countries, as well as for all countries with market economies. The world oil price shown is the refiner acquisition cost of imported crude oil in the United States (in 1985 U.S. dollars per barrel). Since 1977 the data are plotted quarterly. Prices are converted into constant dollars using the gross national product deflator.

Table 1. Net Oil Imports and Their Relation to Export Earnings For Eight Developing Countries, 1973–1984

	1973	1974	1977	1979	1981	1983	1984
				Net Oil Imports (million U.S. dollars, current prices)			
Kenya	1	27	57	113	316	208	219
Zambia	11	30	53	72	63	274	454
Thailand	173	510	806	1,150	2,170	1,740	1,480
Korea	276	967	1,930	3,100	6,380	5,580	5,770
Philippines	166	570	859	1,120	2,080	1,740	1,470
Brazil	986	3,230	4,200	6,920	11,720	8,890	7,470
Argentina	83	328	338	351	302	–	–
Jamaica	71	193	242	309	490	–	–
India	308	1,170	1,750	3,067	–	–	–
Bangladesh	–	92	172	247	509	286	314
Tanzania	47	153	102	174	306	175	156
				Imports as Percentage of Export Earnings			
Kenya	0.1	4.1	4.8	10.2	26.9	21.2	20.3
Zambia	2.2	5.1	9.5	8.2	7.8	20.8	21.4
Thailand	11.1	20.9	23.1	21.6	30.9	27.3	20.0
Korea	8.6	21.7	19.2	20.6	30.0	22.8	19.7
Philippines	8.8	20.9	27.5	24.4	36.8	35.4	27.8
Brazil	15.9	40.7	34.7	45.4	50.4	40.6	27.7
Argentina	2.5	8.3	6.0	4.5	3.3	–	–
Jamaica	18.1	27.3	32.4	37.7	50.3	–	–
India	10.6	29.7	27.5	39.3	–	–	–
Bangladesh	–	26.5	36.1	37.4	64.6	39.4	33.6
Tanzania	12.8	38.0	20.2	34.8	52.7	47.0	42.3

Source: International Monetary Fund, 1985

Figure 2. Long Term and Recent (Insert) Electricity Price Trends for the United States



Prices were converted to constant 1985 cents per kilowatt hour using the gross national product deflator.

I. Some Surprises on the Demand Side

A Quiet Revolution in the Making

As painful as the energy crises of the 1970s were, they led to a fundamentally new approach for managing energy problems, one that offers the hope of avoiding recurring energy crises. For the first time, energy decision-makers turned from the historical preoccupation with expanding energy supplies to examine how energy can be used more effectively in providing such services as cooking, lighting, space heating and cooling, refrigeration, and motive power. Decision-makers have found that energy services can be provided cost-effectively with much less energy than previously thought necessary, and as a result the historical close correlation between the level of energy use and economic well-being has been broken. This revolutionary development has not been reported in dramatic stories in newspapers and magazines because it is not the result of any big government or industry energy projects. Rather, this development is a quiet revolution in which not one but myriad solutions to the energy problem are being found, each matched to one of many energy end uses. Moreover, the "revolutionaries" are not just corporate heads of energy supply companies and government officials, they are a much more diverse community: manufacturers of energy-using appliances and motor vehicles, builders of residential and commercial buildings, factory owners, homeowners, and others.

Consider some recent accomplishments. In the United States the average fuel economy of new cars and light duty trucks increased 66 percent between 1975 and 1985; by 1985, resulting fuel savings were equivalent to 2.4 million barrels per day (mbd) of oil, or nearly 60 percent of U.S. oil imports. In Sweden, the already energy-efficient steel industry, which accounts for about one fifth of Swedish manufacturing energy use, reduced its energy requirements per tonne of steel produced by one fourth between 1976 and 1983. In Japan, where refrigerators account for about 30 percent of residential electricity use, energy requirements for the average new refrigerator were reduced two thirds between 1973 and 1982.[4]

The aggregate results of such improvements have been impressive for the countries of the Organisation for Economic Co-operation and Development (OECD). Oil use in OECD countries fell 15 percent, or 6.1 mbd between 1973 and 1985. In the same period, total energy use per capita for OECD countries fell 6 percent, while per capita gross domestic product (GDP) increased 21 percent. Some countries have made even more impressive advances. Per capita energy use in the United States fell 12 percent while per capita GDP rose 17 percent. In Japan, a 6-percent reduction in per capita energy use was accompanied by a 46-percent increase in per capita GDP in this period.

Future Possibilities

Does the experience of OECD countries since 1973 represent a new trend or just a one-time adjustment to the energy price increases since 1973? Strong evidence suggests that the current technological revolution in energy efficiency may persist for decades, because the most efficient technologies now commercially available or under development far outperform existing technologies.

In 1986, the most energy efficient four-passenger automobile available was the 1986 Chevrolet/Suzuki Sprint, which has an on-the-road fuel economy of 57 miles per gallon (mpg) (4.1 liters/100 kilometers [lhk]), making it nearly three times as efficient as the average car in use in the world. In both the United States and Sweden, new superinsulated houses require just one tenth as much energy for heating as the average house. *(See Figure 3.)* Energy-efficient electrical devices now available include: heat-pump water heaters that use one third the energy of ordinary electric resistance water heaters, air conditioners that use less than one half the energy required by typical units now in use, variable-speed controls for motors that reduce electricity requirements for fans, pumps, and other motive power uses by 20 to 50 percent, and new lighting technologies that can cut lighting electricity use in commercial buildings by 50 percent or more.

Among other advanced technologies, the Elred and Plasmasmelt steelmaking processes under development in Sweden would reduce energy requirements one third or more relative to what the Swedish steel industry has already achieved. In 1986, Toyota unveiled a prototype car for four or five passengers with a fuel economy of 98 mpg (2.4 lhk). *(See Figure 4.)*

Many of these technologies are now economically attractive on a life-cycle cost basis. Nonetheless, some will not be readily adopted because more efficient technologies tend to require extra first costs, which many consumers resist paying even if longer-term savings are high. In such cases, public policies may be needed to promote commercial adoption.

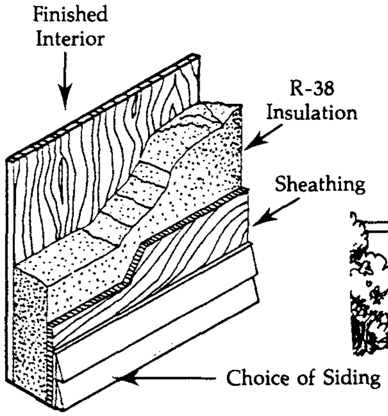
A trend is now developing toward new energy-efficient technologies that are "smart" and attractive for many reasons. These technologies will be more readily adopted than those offering only an energy-saving benefit. History shows that the technologies that succeed commercially have broad appeal. Technical change faces some resistance, but generally such resistance fades if a new technology has many clear advantages over the old.

In industry, the successful new processes have generally been those that simultaneously reduced various costs—for labor, materials, and energy, for instance.[5] This tendency has been so powerful that major improvements in energy efficiency have often been made even in periods of constant or declining energy prices. Such was the case in several important basic industries in the United States between the end of World War II and the first energy crisis. *(See Table 2.)*

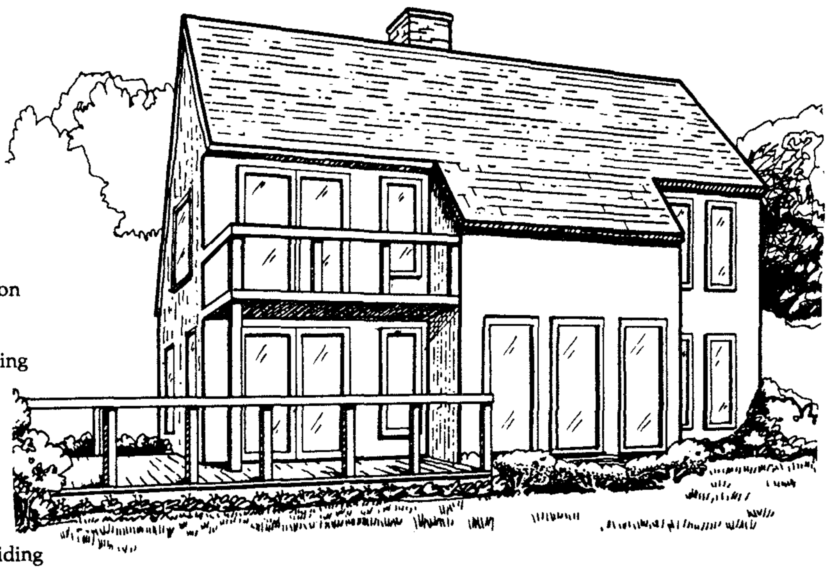
For consumer products too, those most likely to succeed are ones that offer consumers several appealing attributes. Developments in lighting illustrate this point. Lighting efficacy (measured in lumens per Watt) has improved almost a hundredfold since Thomas Edison's initial invention. *(See Figure 5.)* Lighting technology continually improved as electricity prices were plunging. *(See Figure 2.)* Changes were motivated primarily by consideration of such features as durability and light quality, but they incidentally led to improved energy efficiency as well. Rising electricity prices are now a strong incentive to make more improvements, and the opportunities for further improvements are substantial.

The development of compact fluorescent bulbs illustrates the trend toward energy-efficient technologies that are "smart." Fluorescent lights used mainly for commercial and industrial applications have efficacies several times those of the incandescent bulbs used in

Figure 3. Cross-Section of a "Stress-Skin" Panel (Left) Used in a Northern Energy Home (Right)



Stress-Skin Panel



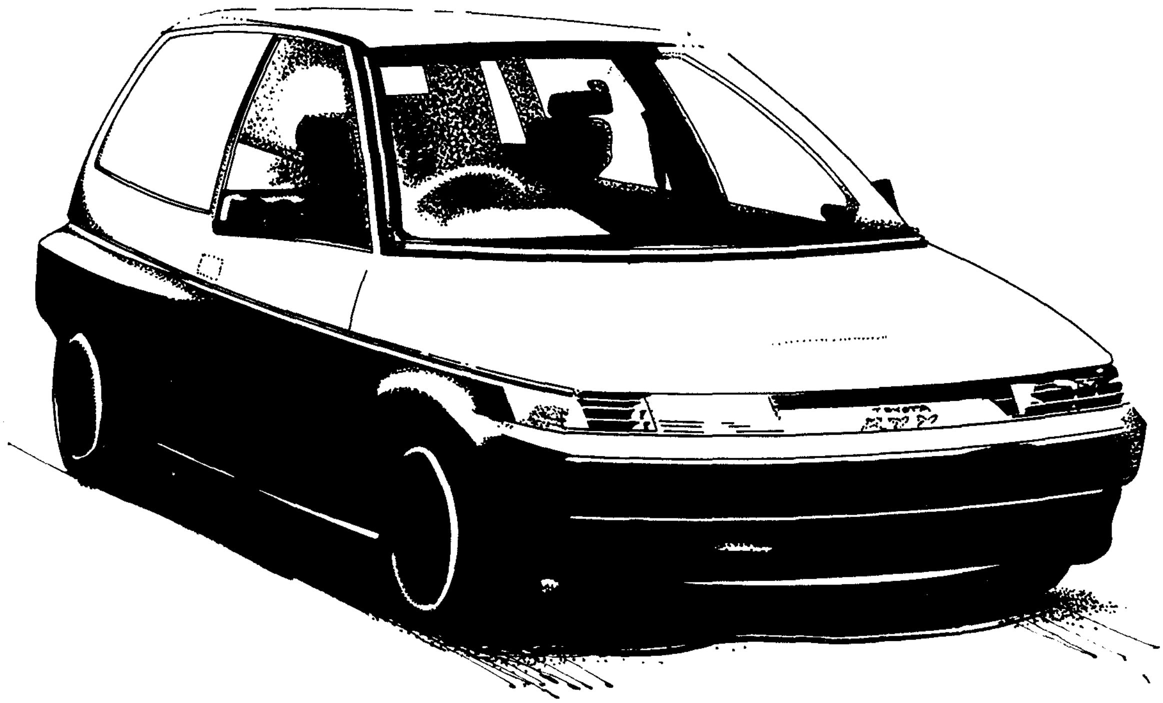
Northern Energy Home

Highly insulating "stress-skin panels" are featured in some super-insulated houses ("Stress-Skin Panels," *Progressive Builder* [September 1986]: 23-26), such as the Northern Energy Home (NEH) offered in the northeastern United States. At the construction site, 4 feet x 8 feet (1.2 meters x 2.4 meters) stress-skin panels are mounted on a post-and-beam frame. The factory-assembled panels, containing thick (8-inch [20-centimeters]) rigid polystyrene insulation, are made to fit together easily for rapid construction. Doors and windows are foam-sealed into the panels at the factory. Because of the tight construction, natural air infiltration is low, so that forced ventilation is used with a heat exchanger that extracts heat from the stale exhaust air and warms the fresh incoming air.

The extra costs for insulation and forced ventilation are more than offset by various savings. Prefabrication of the panels leads to time and labor savings in construction. In addition, temperatures can be kept uniform throughout the house with a couple of small space heaters, which cost much less than a central furnace with ductwork. For a ranch-style NEH with a floor area of 1,300 square feet (120 square meters) in the New York City area, the annual fuel cost for natural gas would be less than $50 per year—compared to more than $400 per year for heating the average house in the Middle Atlantic region of the United States.

most homes. Compact fluorescent bulbs, high-efficacy bulbs that can be screwed into sockets designed for incandescent bulbs, were introduced in the 1970s. The first of these bulbs emitted a harsh white fluorescent light that many consumers dislike in the home. They were also bulky and difficult to fit into many lamps, and they did not have the "instant on" feature that consumers have come to expect. However, these problems have been largely overcome during the last several years. *(See Figure 6.)* The most recently introduced bulb (available in Europe) has a soft yellow light like that of an incandescent, is nearly as small as the incandescent it would replace, illuminates nearly instantly, and will last six times as long as an incandescent.

Figure 4. The Toyota AXV, a Prototype Four- to Five-Passenger, Super Fuel-Efficient Car



Toyota AXV

Introduced in late 1985, the AXV has a fuel economy of 2.4 lhk (98 mpg) on the combined urban/highway test administered by the U.S. Environmental Protection Agency. For comparison, the average U.S. automobile gets about 12.4 lhk (19 mpg), and the average car in the rest of the world about 9.8 lhk (24 mpg). High fuel economy is achieved with the systematic application of presently available technologies: low weight (650 kg [1,430 lb]) from extensive use of plastics and aluminum, low aerodynamic drag, a direct-injection diesel engine (the kind used in trucks), and a continuously variable transmission.

Source: Toyota press release, October 23, 1985.

Relevance to Developing Countries

Rich countries can save far more energy than poor countries by adopting more efficient energy-using technologies. Industrialized countries consume 70 percent of the world's energy. Yet, it does *not* follow that little energy can be saved in developing countries. The elite in these countries—industrialists, commercial traders, landlords, government and military officials, bureaucrats, professionals, and some skilled craftsmen—account for 10 to 15 percent of the population, but one third to one half of income and most commercial energy use. These elites have acquired the energy-using

Table 2. Pre-Energy Crisis Trends in Energy Intensities for Selected Basic Materials in the United States

Material	Period	Average Rate of Decline in Energy Use per Tonne Produced (percent per year) Final Energy[a]	Primary Energy[b]
Raw Steel	1947–1971	1.41	1.19
Portland Cement	1947–1971	1.17	1.09
Chlorine[c]	1947–1971	0.40	0.42
Aluminum[d]	1954–1971	2.83	1.89

Source: R.H. Williams, E.D. Larson, and M.H. Ross, "Materials, Affluence, and Industrial Energy Use," *The Annual Review of Energy* 12(1987): 99–144

a. With electricity counted as 3.6 megajoules per kilowatt hour of electricity consumed.

b. Here electricity is expressed as the fuel required to produce it in a thermal power plant.

c. For 1 tonne of chlorine plus 1.13 tonnes of caustic soda in 50 percent solution.

d. Electricity use per kilogram of primary aluminum declined 0.4 percent per year during this period.

habits of consumers in rich countries, and often they waste even more energy.

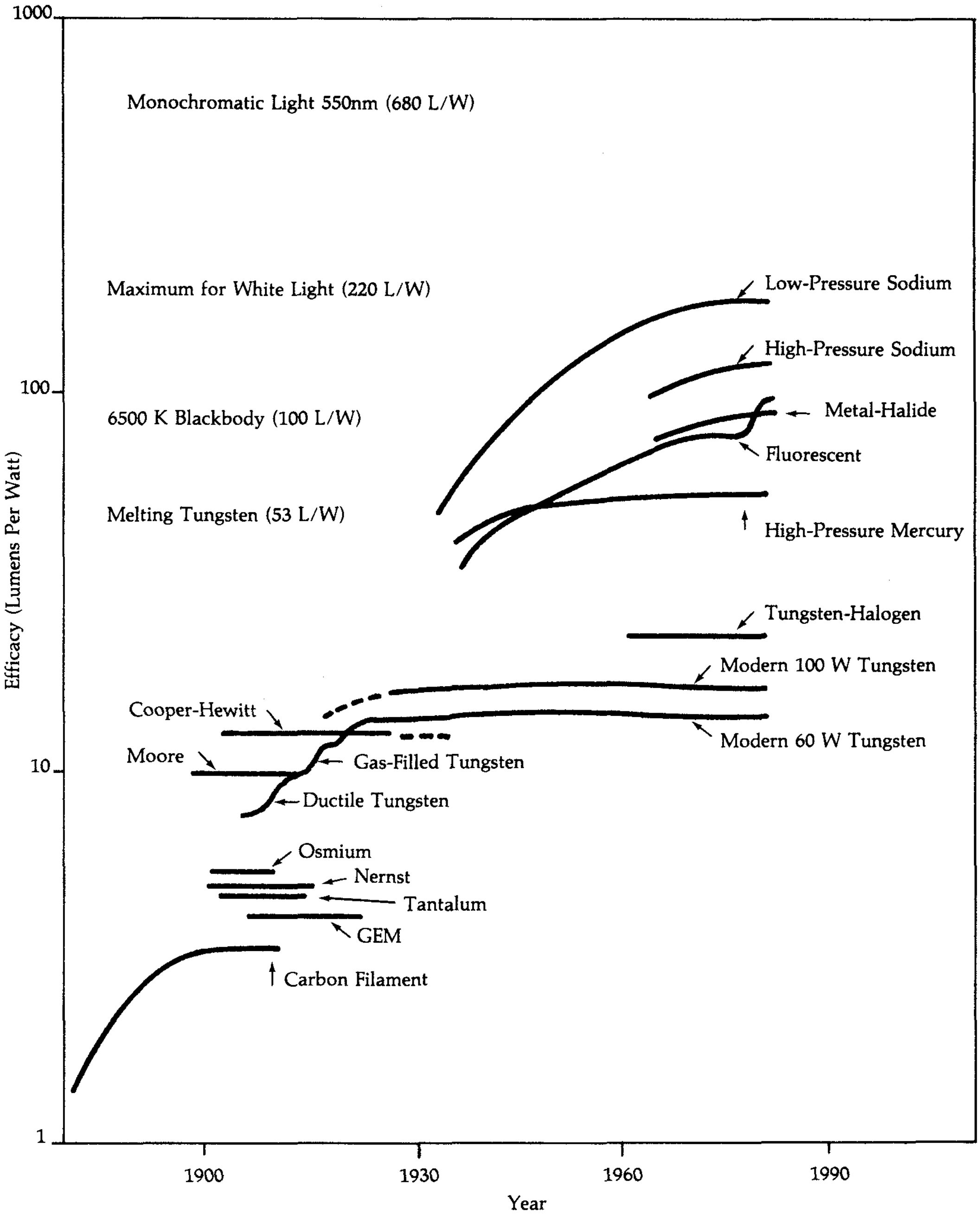
For example, two-door refrigerator-freezers are now becoming popular among Brazil's elite. The new Brazilian units are smaller (340 to 420 liters) than typical units in the United States (500 liters). Yet the Brazilian two-doors consume between 1,310 and 1,660 kWh per year while new U.S. units consume only 1,150 kilowatt hours (kWh) per year (as of 1983). Moreover, the most efficient U.S. model, introduced in March 1985, is a 490-liter frost-free unit requiring only 750 kWh per year. Ironically, this unit achieves its efficiency in large part by using a compressor imported from Brazil: the manufacturer exports a high-efficiency line and markets a less efficient product at home.

In developing countries even poor households, which depend largely on non-commercial biomass fuels and have few if any modern amenities, tend to use energy inefficiently. The poor who use wood for cooking consume three to ten times as much energy per capita as consumers in developing or industrialized countries who have access to modern energy carriers. *(See Figure 7.)* In fact, they use about as much fuel per capita for cooking as Western Europeans use for automobiles.

Fortunately, recent successes in applying heat transfer and combustion principles have led to new highly efficient wood-burning stoves.[6] These new designs, along with standardized testing and production techniques, have made it possible to introduce various low-cost wood stoves compatible with a wide range of cultural settings. *(See Figure 8.)*

Further efficiency gains would result from shifting to modern gaseous or liquid fuels: biogas, producer gas, natural gas, liquid petroleum gas (LPG), and ethanol. Simple stoves based on such fuels can be 50-percent efficient, while even the best available wood

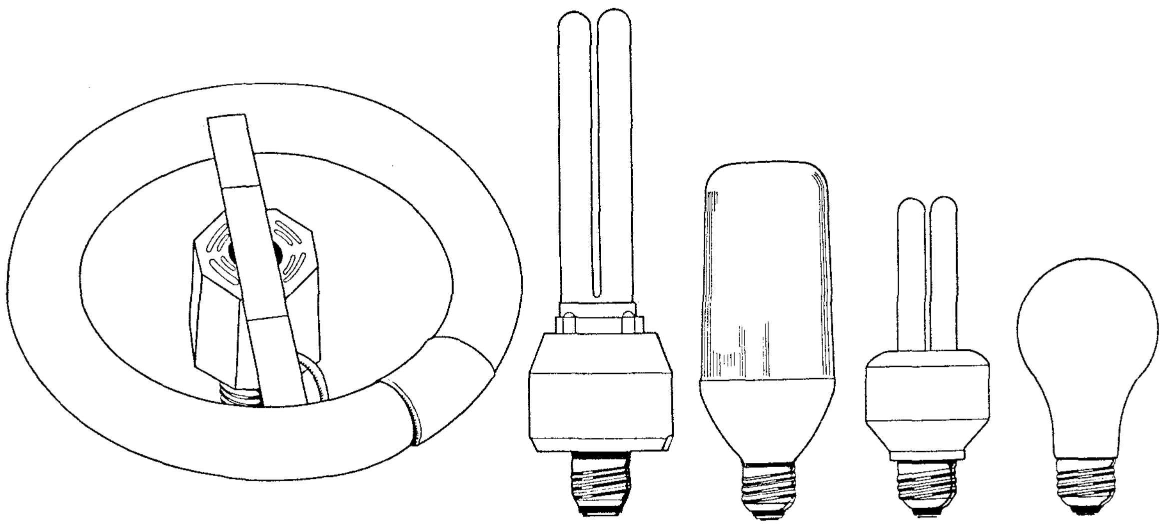
Figure 5. Changes in the Efficacies of Various Light Sources Over Time



This plot shows the evolution of lighting performance within each technology as well as the progress from one technology to another. The efficacies for several standard sources are indicated for comparison.

Source: J.M. Anderson and J.S. Saby, "The Electric Lamp: 100 Years of Applied Physics," *Physics Today* (October 1979): 32-40.

Figure 6. The Rapidly Changing Technology of Compact Fluorescent Lightbulbs



In recent years manufacturers have been steadily improving the compact fluorescent light bulbs that can be screwed into ordinary incandescent sockets. These bulbs have efficacies in the range of 40 to 60 lumens per Watt, compared to 11 to 16 lumens per Watt for ordinary incandescent bulbs. Although the first-generation "circline" bulb (on the left) is efficient, it is bulky (it weighs 1 pound [454 grams] and is 8 inches [20 centimeters] across) and thus does not fit easily into many lamp holders. The harsh white light of the circline is also considered inappropriate for many household applications. Finally, there is a lag after the switch is flicked before the light comes on—an annoying feature for those accustomed to the instant-on feature of incandescents. Each of the three bulbs to the right of the circline incorporates innovations that deal with one or more of these problems. The bulb shown next to the incandescent on the right, manufactured by Osram and now being sold in Europe, has none of the drawbacks of the earlier bulbs. It provides as much light as a 60-Watt incandescent drawing only 11 Watts and lasts six times as long. It weighs just 4 ounces (114 grams) and fits into most incandescent lamp holders. The phosphor coatings on the inside of the bulb give rise to a light quality similar to that for incandescents. For the impatient, the light is instant-on.

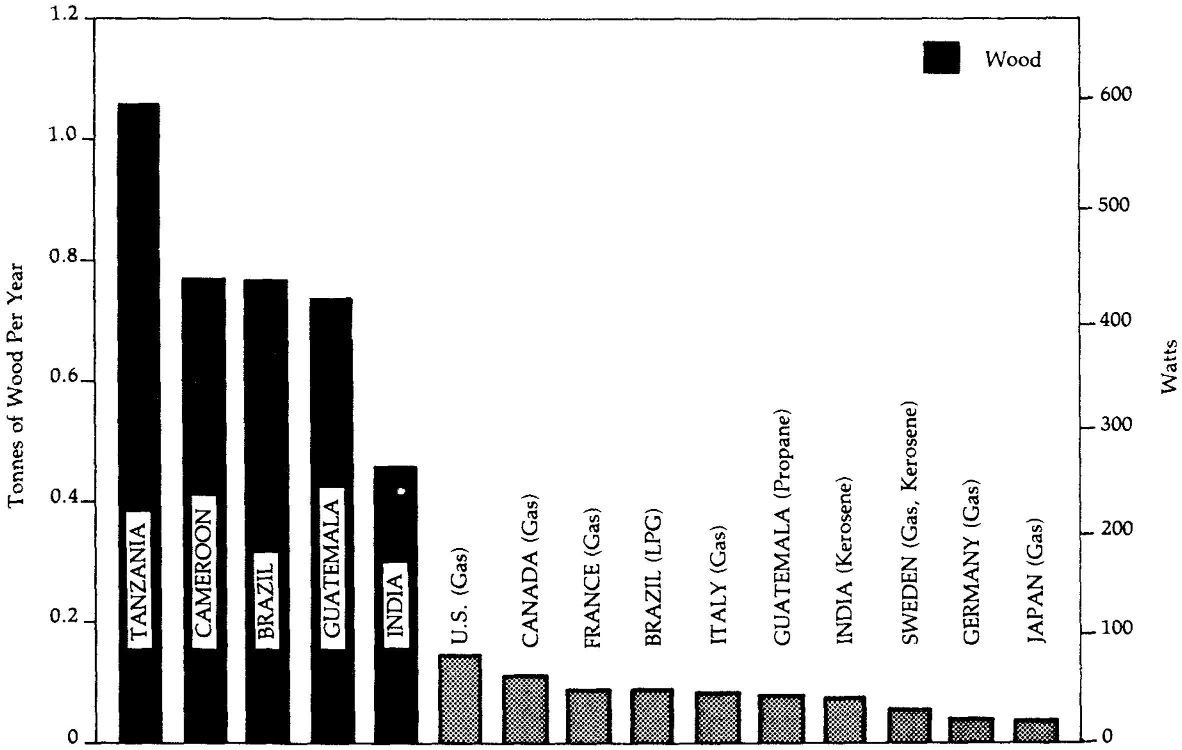
stoves have efficiencies of only 30 to 40 percent.

Shifting biomass sources to produce modern fluid fuels can so significantly reduce biomass feedstock requirements for cooking that extra biomass would be available for other uses. They could include water pumping and rural electrification based on producer gas engine sets, which produce gas from biomass feedstock and convert it to mechanical power or electricity in modified gasoline or diesel engine sets. *(See Box 1.)* The biomass available for such purposes would increase, if the gas stoves were more efficient. One especially efficient gas stove has just been developed. *(See Box 2.)*

Adding It Up

To indicate how significant technological opportunities like those described above are, we have constructed a global energy scenario for the year 2020 that focusses on energy end uses. We examined in detail how energy is

Figure 7. Per Capita Energy Use Rates for Cooking With Wood and High-Quality Energy Carriers



For both wood stoves and stoves using high-quality energy carriers, the per capita energy use rate is expressed in Watts (an abbreviation for Watt-years per year). For wood it is also given in tonnes of dry wood per year, assuming 1 tonne of wood = 18 gigajoules, so that 1 tonne per year = 570 Watts.

Source: J. Goldemberg, *et al.*, "Basic Needs and Much More with 1 kW per Capita," *Ambio* vol. 14, no. 4-5 (1985): 190-200.

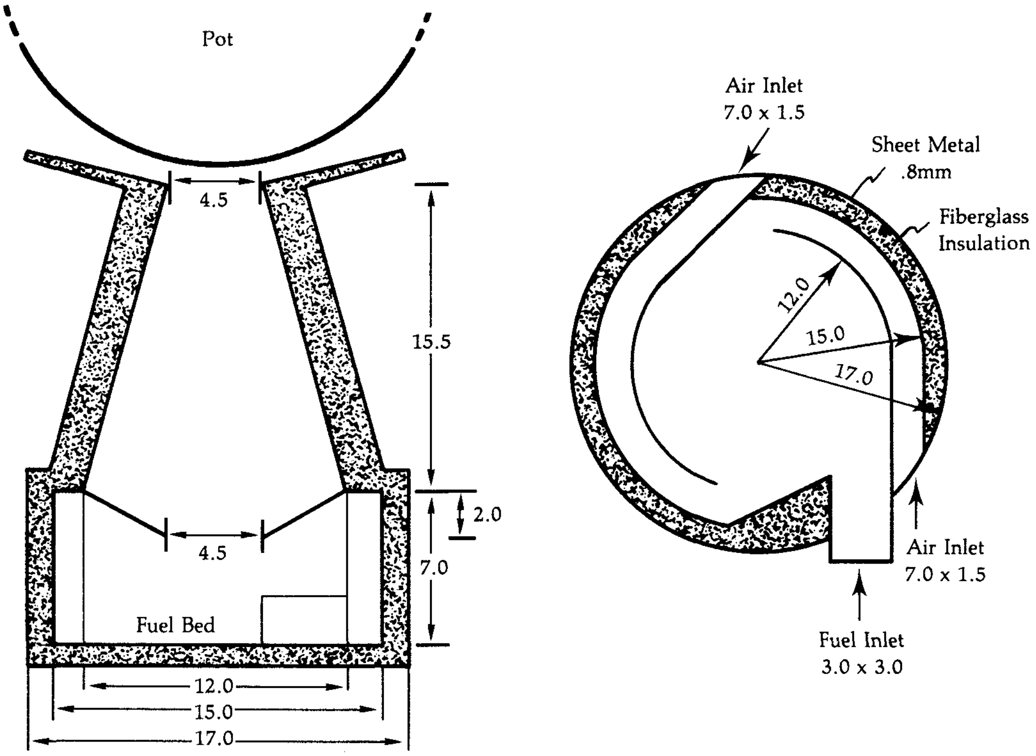
now used, identified ongoing structural economic changes that will shape energy demand, and explored technically and economically feasible ways to use energy more efficiently.

Our analysis indicates that the global population could roughly double, that living standards could be improved far beyond satisfying basic needs in developing countries, and that economic growth in industrialized countries could continue, without increasing the level of global energy use in 2020 much above the present level. The level of global energy use identified in our scenario is far below the doubling or tripling of global energy use projected in conventional energy analyses. *(See Figure 9.)*

Our scenario is not a prediction but, rather, a statement of what is technically and economically feasible. It could come about, facilitated by appropriate public policies.

Yet, why should attention be given to alter-

Figure 8. A High-Efficiency Wood Stove Designed by Applying Modern Scientific and Engineering Principles to the Cooking Task



Cross Section
Viewed From the Side
(Dimensions in Centimeters)

Cross Section of the Bottom
Viewed From Above
(Dimensions in Centimeters)

Recent applications of the principles of heat transfer and combustion to fuelwood cooking stove design have resulted in simple, highly efficient stoves. Typically such improved stoves can pay for themselves in fuel savings within a few months.

The stove shown here, made of sheet metal and insulation, is under development at the Indian Institute of Science at Bangalore. The efficiency of this stove can be more than 40 percent compared to less than 20 percent for protected open fires. Hazardous smoke emissions would also be greatly reduced with this type of stove.

Good performance is due to the use of insulation to reduce heat loss through the walls; a unique combustion chamber design that promotes mixing of air with and recirculation of unburned volatiles until combustion is complete; and a narrowing combustion chamber and a narrow pot-to-stove channel width to increase the gas velocities over the bottom and sides of the pot, thereby improving the heat transfer to the pot.

Source: H.S. Mukunda and U. Shrinivasa, "Single Pan Wood Stoves of High Efficiency, Part I," July 1985; H.S. Mukunda, *et. al.*, "Single Pan Wood Stoves of High Efficiency, Part II," December 1985 (Bangalore, India: Indian Institute of Science), Centre for the Application of Science and Technology to Rural Areas.

Box 1. Producer Gas Technology

If biomass is to be an important energy source for development, it must be used much more efficiently than in the past, and it must be converted increasingly to modern energy carriers such as gas and electricity. "Producer gas" is one of several biomass-derived modern energy carriers. Through the partial oxidization of the biomass feedstock in air, a gas can be produced that consists largely of carbon monoxide, hydrogen, and nitrogen. Producer gas can be made in low-cost converters at an overall energy efficiency of 60 to 70 percent or more. The energy losses in conversion are usually more than offset by the energy savings of the more energy-efficient end-use devices that can be used with gas.

At present, the most common application of producer gas is to displace oil or natural gas in industrial boilers. It can also be used for cooking or to produce electricity in small engine-generator sets for agricultural pumping, village electrification, or rural industry. Producer gas was widely used in World War II as a gasoline substitute in automobiles fitted with wood- or charcoal-fired producer gas engines. Today, when electricity is generated using producer gas as fuel, the converter employed is often a modified automobile engine.

Interest in producer gas was revived in the 1970s, and many gasifiers are now operating in developing countries. Charcoal is currently favored over wood or other raw biomass feedstocks for engine applications because the produced gas is tar free and less likely to cause engine trouble than wood-derived gas, and it does not require costly gas cleanup techniques. However, the large difference between charcoal and raw biomass prices limits the economic attractiveness of charcoal gasification. In addition, gasifying charcoal rather than raw biomass is much less resource-efficient. For these reasons, gasifier research and development efforts are beginning to be focussed on producing tar-free gas from wood and other raw biomass sources.*

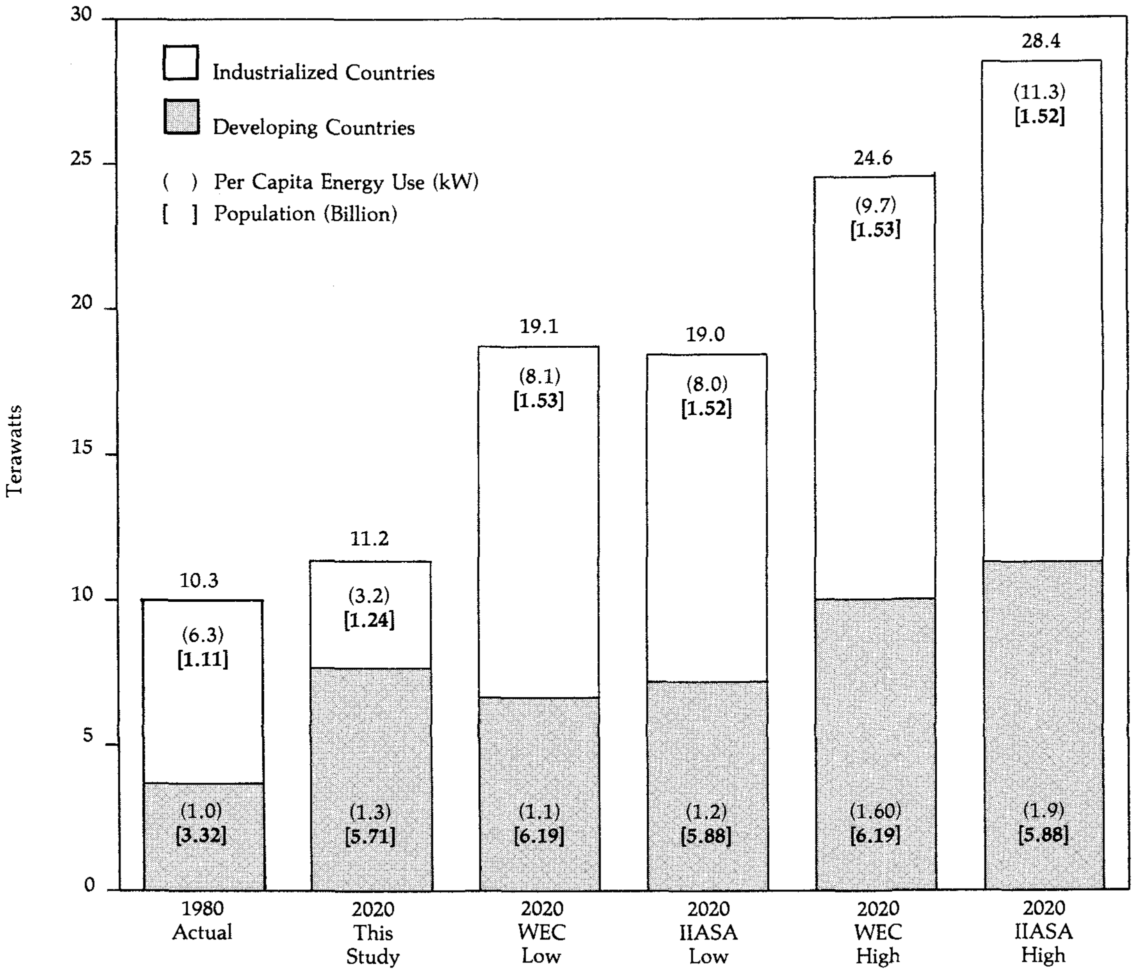
* E.D. Larson, "Producer Gas, Economic Development, and the Role of Research," Rep. No. PU/CEES 187, Center for Energy and Environmental Studies, Princeton University, Princeton, N.J., April 1985.

Box 2. Infrared Impingement Burner

The Thermoelectron Corporation is developing a high-efficiency infrared impingement burner for cooking stoves for the Gas Research Institute. The unit has a measured efficiency of 65 to 70 percent, much higher than the 40- to 50-percent efficiency of conventional gas stoves. In addition, the burner's carbon monoxide and nitrogen oxides emissions are far less than those from conventional units.* This technology exemplifies the trend toward high-efficiency products that have attractive features beyond good energy performance, making the products more desirable to consumers.

* K.C. Shukla and J.R. Hurley, "Development of an Efficient, Low NOx Domestic Gas Range Cook Top," Rep. No. GRI-81/0201, Gas Research Institute, Chicago, 1983.

Figure 9. Alternative Projections of Global Primary Energy Use Disaggregated into the Shares Accounted for by the Industrialized and the Developing Countries



Primary energy use in TW (an abbreviation for terawatt-years per year) is shown both for alternative projections to the year 2020 and for 1980. The projections shown are the one constructed in the present study and both the high and low scenarios advanced in the IIASA (W. Haefele, *et al.*, *Energy in a Finite World—A Global Systems Analysis* [Cambridge, Massachusetts: Ballinger, 1981]) and WEC (World Energy Conference, *Energy 2000-2020: World Prospects and Regional Stresses*, J.R. Frisch, ed. [London: Graham & Trotman, 1983]) studies.

"Primary energy" is the energy content of the various sources in naturally occurring forms, before conversion into various useful energy carriers and delivery to consumers as "final energy."

native energy futures and new energy policies? Haven't market forces already solved the energy problem, once more bringing low oil prices and a worldwide oil glut? Is such a low energy future relevant to the needs of the people in either developing or industrialized countries? How different would the world be given the energy future we have described rather than the energy futures usually projected?

II. A Closer Look at the Energy Problem

A Temporary Reprieve for Oil Consumers

The collapse of world oil prices in late 1985 and early 1986 came as good news to the many countries that import oil. *(See Figure 1.)* To many, it seemed to signal the end of the energy crisis and the Organization of Petroleum Exporting Countries' (OPEC) loss of control over the world oil market.

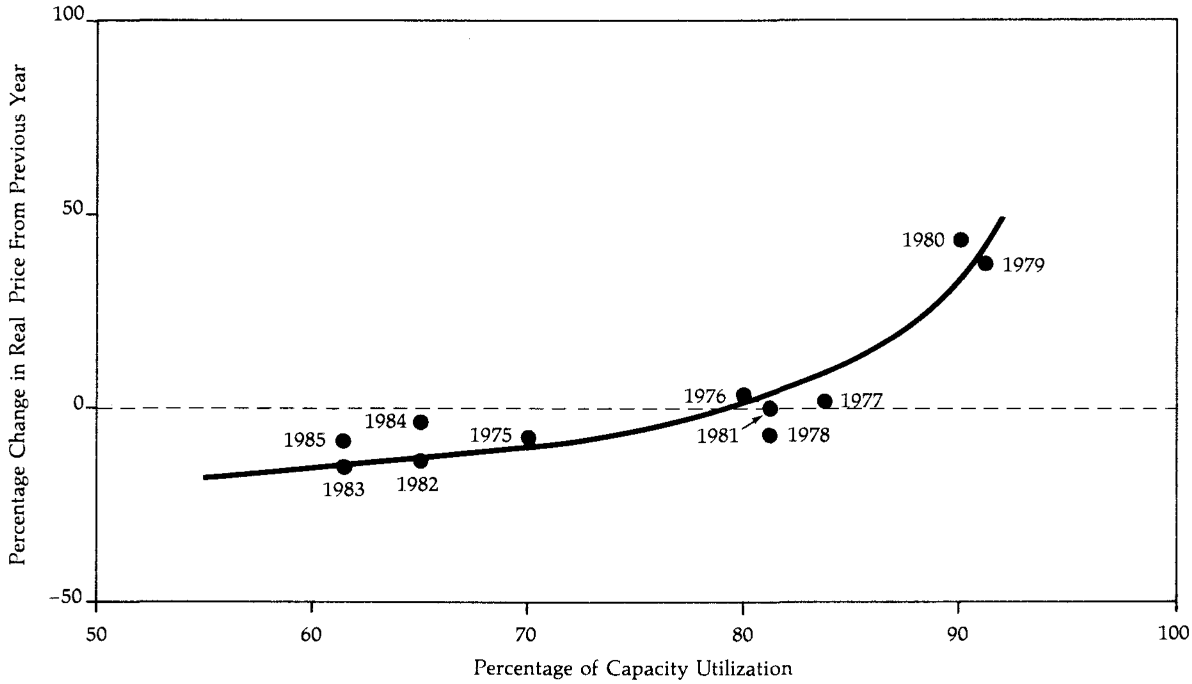
Unfortunately, the decline in the price of oil indicates neither of these outcomes. Oil consumers have been granted only a temporary reprieve.

To understand why, consider the relationship between world oil price and the demand for OPEC oil. *(See Figure 10.)* Between 1975 and 1985, the oil price was rising when demand for OPEC oil was above 80 percent of OPEC production capacity, and they were falling at lower demand levels. Just before the second oil price shock in 1979, as before the first, a surge in oil demand in the industrialized market economies created tight market conditions, enabling OPEC to exercise its monopoly power and raise the price sharply. *(See Figure 1.)* Oil-saving efforts by consuming countries, together with increases in oil production outside OPEC (in the North Sea, Mexico, Alaska, and elsewhere), then transformed the oil market from a sellers' to a buyers' market.

Will oil buyers around the world increase their demand in response to today's lower prices? There is probably no going back to oil-guzzling days. For example, consumers will not pull insulation out of their attics, and many of the more energy-efficient oil-using technologies were adopted for reasons that go beyond fuel savings. It won't take much, though, to put OPEC back in the driver's seat.

The U.S. Department of Energy (DOE) projected in 1985 that net oil imports by OECD countries would increase some 4 million barrels per day between 1985 and 1995, owing about equally to a modest increase in demand and to an expected decline in U.S. oil production.[7] The projected decline in U.S. production reflects not the decline in drilling brought about by the recent sharp drop in the world oil price but, rather, the limits of remaining resources; in fact, the DOE scenario is for a world oil price that returns to $30 per barrel (in 1985 dollars) by 1995. In addition, DOE projects an increase in cil demand by developing countries with market economies of some 2.5 mbd in this period, an increase consistent with recent trends. *(See Figure 1.)* The DOE also projects a drop of about 1 mbd in exports from centrally planned economies, reflecting the expected decline in Soviet oil production. If, as projected, other oil producers expand production only modestly, the increase in demand for OPEC oil would amount to more than 7 mbd. With such an increase, OPEC would again be

Figure 10. OPEC Pricing Behavior, 1975 to 1985



This figure shows the percentage change in the real world oil price from the previous year versus the demand for Organization of Petroleum Exporting Countries (OPEC) oil, expressed as a percentage of OPEC productive capacity used. (The percentage of OPEC capacity used is equal to crude oil production divided by maximum sustainable production.)

At the present level of OPEC production capacity, oil prices would rise again if the demand for OPEC oil increased 5 million barrels per day, equal to about 10 percent of the oil consumption rate for the world's market economies.

Source: U.S. Energy Information Administration, "International Energy Outlook 1985, With Projections to 1995," U.S. Department of Energy, (Washington, D.C., March 1986).

operating at more than 80 percent of capacity. If history is a reliable guide, the world oil price would then be rising. *(See Figure 10.)*

The DOE analysis suggests that several developments, each of which alone would only modestly affect the world oil market, could together tighten that market relatively quickly. Although the real world might not evolve exactly the way envisaged by DOE, that scenario must be close to what would happen under business-as-usual conditions. The ups and downs in oil prices have not changed the essential problem: oil is a relatively scarce commodity of considerable value, two thirds of the world's recoverable oil resources are still controlled by a handful of nations in the Middle East and by the Soviet Union, and no ready oil substitutes exist for fueling automobiles, trucks, airplanes, tractors, and other vehicles. What economists call "the preconditions of cartelization" continue to be very much a reality in the oil market. These conditions differentiate oil from such widely traded commodities as copper, tin, uranium, and cotton.

Although the world oil market will eventually tighten, the day when the oil prices must rise again can be forestalled for years, perhaps decades, by improvements in energy efficiency. For example, if all cars were as fuel-efficient as the Toyota AXV, oil use in the world's market economies would be lower by an amount equal to DOE's projected increase in demand for OPEC oil by 1995. *(See Figure 4.)*

It should come as no surprise that oil-importing countries can keep world oil prices low by consuming less. The 6-mbd reduction in oil demand achieved by the OECD countries between 1973 and 1985 is largely responsible for the present oil glut; if demand were now just this much higher, oil prices would be rising. *(See Figure 10.)*

Energy and Development

Why worry about oil prices' rising again in a decade or so? Arguably, we shall then be richer and better able to afford higher prices. Such thoughts, though, are cold comfort to the three fourths of humanity who live in developing countries. It is their grave misfortune to have to industrialize after the end of the era of cheap energy, upon which the industrial bases of the already industrialized countries were built.

Per capita income in developing countries averages one tenth that in the rich industrialized countries, per capita energy use less than one sixth. Average life expectancy is about 50 years, compared to more than 70 in the industrialized countries. One of every five persons in developing countries suffers from hunger or malnutrition. One of every two has little chance of becoming literate.

If the majority of the world's population that lives in wretched poverty is to achieve a decent standard of living, it will need affordable energy for increasing agricultural productivity and food distribution, delivering basic educational and medical services, establishing adequate water-supply and sanitation facilities, and building and powering new job-creating industries. In addressing the world's energy future, therefore, one question stands above all others: Will people in developing countries get the energy they need to sustain a higher standard of living, equal, say, to that enjoyed by Western Europeans today?

Looked at in conventional terms, the challenge seems formidable. If the average annual growth rate in per capita commercial energy use for developing countries in the 1970s (3.6 percent) were to persist until the year 2020, per capital commercial energy use would then be 2.3 kilowatts (kW), still far less than the average of 4.0 kW for Western Europe in 1975. If, as is expected, the population in developing countries nearly doubles, the resulting aggregate demand for commercial energy would reach 15 billion Watts, or terawatt-years per year, (TW) by 2020, up from 2 TW in 1980. The *increment* in energy use by developing countries in this period would be 1.3 times the world's total energy use in 1980, 3 times its oil production, 5 times its coal production, 7.5 times its natural gas production, nearly 9 times its bioenergy production, and nearly 60 times its nuclear energy production. It would be exceedingly difficult to meet such energy requirements at reasonable costs and without major environmental or security problems.

Outside the Middle East and North Africa, most developing countries have little or no petroleum. Except for China, most have little coal. Their hydropower and biomass resources, though important, appear paltry when compared with the needs implied by a continuation of historical trends.

The cost of expanding energy supplies has been growing steeper, and the outlook is even more grim. The World Bank in 1983 estimated that to achieve a scaled-down 2.5-percent annual growth in per capita commercial energy use from 1980 to 1995, developing countries would require investments in new energy supplies of about $130 billion per year (in 1982 dollars) between 1982 and 1992, or about 4 percent of GDP.[8] Half this investment would have to come out of developing countries' foreign exchange earnings, requiring an average annual increase of 15 percent in real foreign exchange allocations to energy supply expansion. Despite these investments, oil imports by oil-importing developing countries would increase by nearly one third, to almost 8 mbd by 1995. Such a commitment of economic resources is completely unrealistic, particularly given the financial vise in which many developing countries find themselves today, squeezed between high debt costs and low export-commodity prices.

The staggering cost of providing such increases in energy supply has led some analysts to conclude—if rarely to state publicly—that living standards in developing countries simply cannot be substantially improved in the foreseeable future.

This judgment rests on the assumption that to raise their living standards to the Western European level, developing countries will have to increase their energy use to the Western European level. However, large improvements in living standards can be made with little increase in energy use *if* planners take advantage of cost-effective opportunities to use energy more efficiently. For a wide range of energy-using technologies, saving energy will require less capital investment than supplying an equivalent amount by conventional means, freeing up scarce capital for other purposes.

The Other Energy Crisis

The "energy crisis" of 1973 to 1981 brings to mind the message Mark Twain wired from Vienna on his first visit to that city: "Vienna isn't what it used to be and never was."

The energy crisis has been seen almost exclusively as a problem of oil and the other modern energy forms that shape life in industrialized countries and in modern sectors of developing countries. But more than half the people in the world live in villages and small towns in Asia, Africa, and Latin America, where modern energy forms are little used. In particular, many villagers cannot afford oil products—diesel fuel, gasoline, liquid petroleum gas (LPG), or kerosene—or the things those products run. For these people, dependent largely on fuelwood and other biomass forms, the energy crisis did not fade with the onset of the recent world oil glut; it worsened.

People are burning wood more rapidly than it is grown, and increasing amounts of human energy and time are spent gathering and hauling fuelwood. The United Nations Food and Agriculture Organization estimates that some 100 million human beings now suffer an acute scarcity of fuelwood and about 1 billion have a fuelwood deficit. At present consumption rates, the annual fuelwood deficit will more than double between 1980 and 2000, from 407 to 925 million cubic meters (m3). Current tree-planting rates are only about 1 percent of what is required to reverse this trend, and many of the planted trees don't survive.

The increasing pressure on wood resources by a rapidly growing population of poor people who must rely on fuelwood to heat and light their homes and cook their food has had serious environmental repercussions. In several regions, including the Himalayas and the Andes, the cutting of trees and brush on steep slopes lays bare the land, so the soil erodes at catastrophic rates and rainwater runs rapidly off the land, increasing flooding downstream. In dry regions, fuelwood harvesting has become a major cause of desertification, along with overgrazing by livestock and dryland farming. The environmental effects of fuelwood harvesting have been especially severe in sub-Saharan Africa. The hardest hit countries include Ethiopia, Sudan, Mali, Chad, Niger, Mauritania, Burkina Faso, Kenya, Somalia, and

Tanzania. Each year human overuse leads to the worldwide loss of some 20 million hectares (50 million acres) to desertification—an area roughly the size of Senegal.

An important development goal should be to reverse the process of deforestation and desertification, preserving land and soil resources for economic activities, wilderness, and wildlife habitats.

One important use of these resources would be the production of biomass for energy purposes. Biomass is the most widely available energy resource in developing countries, and in fact it accounts for more than 40 percent of total energy use there. *(See Table 3.)*

If biomass is to be an environmentally acceptable energy resource, however, it must be produced on a renewable basis. And if biomass is to make a significant energy contribution to development, it must be made more abundant and used much more efficiently.

More biomass can be made available if it is produced in highly productive woodlots, energy farms, or energy plantations instead of merely being harvested from natural forests, which have relatively low productivity.

Table 3. Summary of Selected National Energy Consumption Surveys

Country	**Commercial Energy**	**Non-Commercial Energy** (kilowatts per capita)	**Total Energy**	**Percentage of Energy from Non-Commercial Sources**
Bangladesh	0.038	0.095	0.133	71
Niger	0.035	0.254	0.289	88
Gambia	0.098	0.222	0.320	69
Morocco	0.267	0.073	0.340	21
India	0.165	0.190	0.355	54
Ethiopia	0.019	0.371	0.390	95
Nepal	0.009	0.429	0.438	98
Somalia	0.092	0.476	0.568	84
Bolivia	0.340	0.263	0.603	44
Sudan	0.159	0.635	0.794	80
Thailand	0.305	0.524	0.829	63
Tanzania	0.060	0.810	0.870	93
China	0.778	0.317	1.10	29
Brazil	0.737	0.371	1.11	34
Mexico	1.29	0.127	1.43	9
Libya	1.76	0.095	1.86	5
Developing Countries (average)	0.550	0.416	0.966	43

Source: Adapted from D.O. Hall, G.W. Barnard, and P.A. Moss, *Biomass for Energy in Developing Countries* (Oxford: Pergamon Press, 1982), Table 2-3.

Making efficient fuelwood cooking stoves widely available is important in the near term to making scarce fuelwood supplies go farther. *(See Figure 8.)* For the longer term, it is important to convert biomass into high-quality gaseous fuels (biogas or producer gas), liquid fuels (methanol or ethanol), or electricity so that much more useful energy can be extracted from a given biomass feedstock than is possible with traditional combustion technologies. A shift to such high-quality biomass energy forms, which could substitute for imported oil, would make the biomass more valuable and thus more profitable as a crop.

The Hidden Costs of Conventional Energy

Since the late 1960s, the environmental and security risks associated with the production and use of conventional commercial energy forms have been important considerations in energy planning.

In some instances, it is possible to limit these risks with a variety of control technologies. For example, various devices have been employed to reduce harmful air pollutant emissions from fossil-fuel burning power plants and automobiles.

But for some serious problems, simple technical fixes such as emissions-control devices do not exist, and risk reduction can be achieved only by limiting dependence on the troublesome technology. Three such problems stand out as particularly worrisome: global insecurity arising from industrialized countries' overdependence on Middle East oil, the potential for global climate change owing to build-up in the atmosphere of carbon dioxide (CO_2) from burning fossil fuels, and the threat of nuclear weapons proliferation that accompanies the spread of nuclear power around the world.

Global Insecurity and Middle East Oil. If the world once more becomes hungry for OPEC oil, the resulting higher world oil price would be only one cost. In addition, efforts by the industrialized market countries to assure continued access to Middle East oil supplies in times of crisis could make the world a much more dangerous place. The importance of assured access to these oil supplies was articulated by U.S. Defense Secretary Caspar Weinberger:

> *The umbilical cord of the industrialized free world runs through the Strait of Hormuz and into the Persian Gulf and the nations which surround it. . . .*

That Middle East conflicts can engage the superpowers and even threaten nuclear war is indicated by the experience of October 1973, when the Soviet Union threatened to intervene in the Arab-Israeli War and the United States, in response, put its nuclear forces on alert. U.S. anxiety about the possible course of events around the Persian Gulf led it to organize a Rapid Deployment Force that could occupy strategic areas in the region or confront any expeditionary force the Soviet Union might introduce in case of revolution or war there.

The global security risk inherent in this situation can be reduced if the industrialized market economies avoid becoming too dependent again on Middle East oil. Adopting oil-efficient technologies is the most effective way of achieving this goal. Very efficient cars should be regarded not just as attractive consumer products but also as indirect deterrents of war, even nuclear war.

Global Climatic Change and Fossil Fuel Use. Within decades, we could see a general warming of the earth's surface and other major changes in the global climate because of CO_2 buildup in the atmosphere and the resulting "greenhouse effect."[9] The amount of CO_2 in the earth's atmosphere is now more than 15 percent higher than in pre-industrial times. With continued emphasis on expanding fossil fuel use in energy planning, the CO_2 content of the atmosphere would double in 50 to 100 years.

Higher CO_2 concentrations in the atmosphere will almost certainly cause a global warming. Carbon dioxide in the atmosphere, though transparent to incoming solar radiation, prevents the escape of heat (infrared) radiation from the earth. The precise extent and effects of this warming are less certain. Global climate models, however, indicate that a doubling of atmospheric CO_2 would raise the average temperature at the earth's surface by $3° \pm 1.5°C$—enough to invite potentially devastating consequences. Moreover, the heating effects of the CO_2 build-up are being amplified by a roughly comparable amount of heating owing to the atmospheric build-up of other trace gases (methane, chlorinated fluorocarbons, etc.), which increases the urgency of the problem.

With continued expansion of fossil fuel use, the CO_2 content of the atmosphere would double in 50 to 100 years.

Any warming would not be uniform but would instead be much greater at the poles. This differential warming would slow down the "atmospheric heat engine" that is driven by the equatorial-polar temperature difference and would surely change weather patterns (including rainfall distribution).

No technical solution to the CO_2 problem is known. The only way to mitigate the problem is to reduce combustion of fossil fuels, which account for about four fifths of global energy use. Because remaining coal resources are far greater than remaining oil and gas resources combined, finding ways to reduce overdependence on coal will become increasingly important.

Several decades from now it may be possible to replace fossil fuels with energy supplies that do not contribute to the atmospheric burden of CO_2. But for now the most promising way to limit the CO_2 build-up is to use energy more efficiently.

Nuclear Weapons Proliferation and Nuclear Power. Nuclear weapons and nuclear power are indissolubly linked. Nuclear power reactors produce substantial quantities of plutonium, a material usable in nuclear weapons. This plutonium becomes much more accessible to would-be weaponmakers when it is recovered from spent reactor fuel and recycled in fresh fuel. If a nation without nuclear weapons acquires plutonium recycling technology, it thereby acquires nearly all the technology and materials needed to make nuclear weapons quickly. There is no way to eliminate the link between nuclear weapons and nuclear power, but the proliferation risk would be much less if plutonium-recycling technologies were not used.

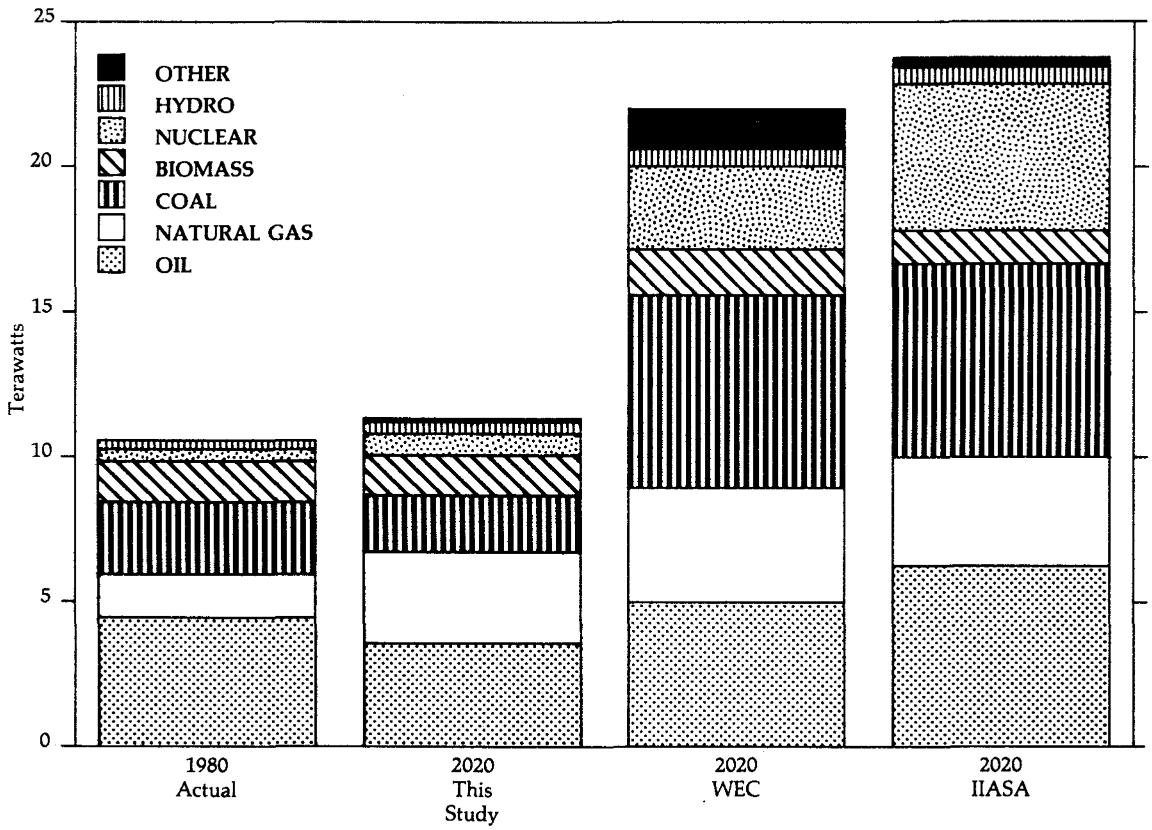
Interest in plutonium recycling arises because without plutonium recycling only about 1 percent of the nuclear energy stored in natural uranium can be used in reactors of present design. With plutonium recycling, the useful energy recoverable from uranium can be increased somewhat with existing reactors. But experience with plutonium recycling in these reactors would facilitate the introduction of plutonium breeder reactors, which could make use of up to 50 percent of the energy stored in uranium. Thus, as uranium supplies become scarcer, interest in plutonium recycling and breeder reactors will increase.

Even though ambitious plutonium recycling programs are under way in France and a few other countries, there is no economic justification for plutonium recycling because uranium prices are low and fuel reprocessing costs are high.[10] If growth in nuclear power were sufficiently modest, plutonium recycling would not be economical for many decades at least.

Avoiding plutonium recycling greatly weakens but does not destroy the link between nuclear weapons and nuclear power. The plutonium in spent fuel produced in nuclear power plants can be a tempting source of nuclear weapons material for countries determined to acquire nuclear weapons. This risk can be reduced only by limiting the overall level of nuclear power development—for example, by regarding nuclear energy as the energy source of last resort.

The most effective way to avoid plutonium recycling technologies and overdependence on nuclear energy over the next several decades is to pursue more efficient energy use. Doing so

Figure 11. Alternative Projections of Global Primary Energy Use Disaggregated into the Shares Accounted for by Various Energy Sources



Primary energy use (in billionWatts, or terawatt-years per year [TW]) is shown both for alternative projections to the year 2020 and for 1980. The projections shown are the ones constructed in the present study and both the high and low scenarios advanced in the IIASA (W. Haefele, *et al.*, *Energy in a Finite World—A Global Systems Analysis* [Cambridge, Massachusetts: Ballinger, 1981]) and WEC (World Energy Conference, *Energy 2000-2020: World Prospects and Regional Stresses*, J.R. Frisch, ed. [London: Graham & Trotman, 1983]) studies. For the IIASA and WEC cases the projections shown are averages of the high and low scenarios described in those analyses.

The convention adopted here for measuring the nonfossil-fuel sources of electricity is that hydroelectricity is counted as the energy available in the produced electricity, and nuclear energy is counted as the heat released in nuclear fission, the process from which the produced electricity is derived.

would also buy time for the development of less dangerous technologies for electricity generation in the future.

Looking Ahead—Reason for Optimism

The low-energy demand scenario made possible by the ''quiet revolution'' in more efficient energy-using technology is attractive under narrow economic criteria: energy services are provided at equal or lower costs than providing the same services with conventional, less efficient end-use technologies and more energy supplies. With demand thus lowered, energy prices would also be lower because there would be less need for Middle East oil and for costly domestic energy sources.

In addition, when energy demand is low, considerable flexibility is gained in energy supply planning, making it possible to avoid the environmental and security problems posed by overdependence on Middle East oil, fossil fuels generally, and nuclear power. We have prepared a supply mix matched to our global low energy demand scenario for the year 2020 to illustrate this flexibility. *(See Figure 11.)* Like our low-energy demand scenario, this supply scenario is not a forecast. It is, however, a plausible energy supply mix not obviously constrained by supply availability or costs. It shows what is economically, technically, and politically possible—in short, what our choices are.

III. Alternative Energy Futures

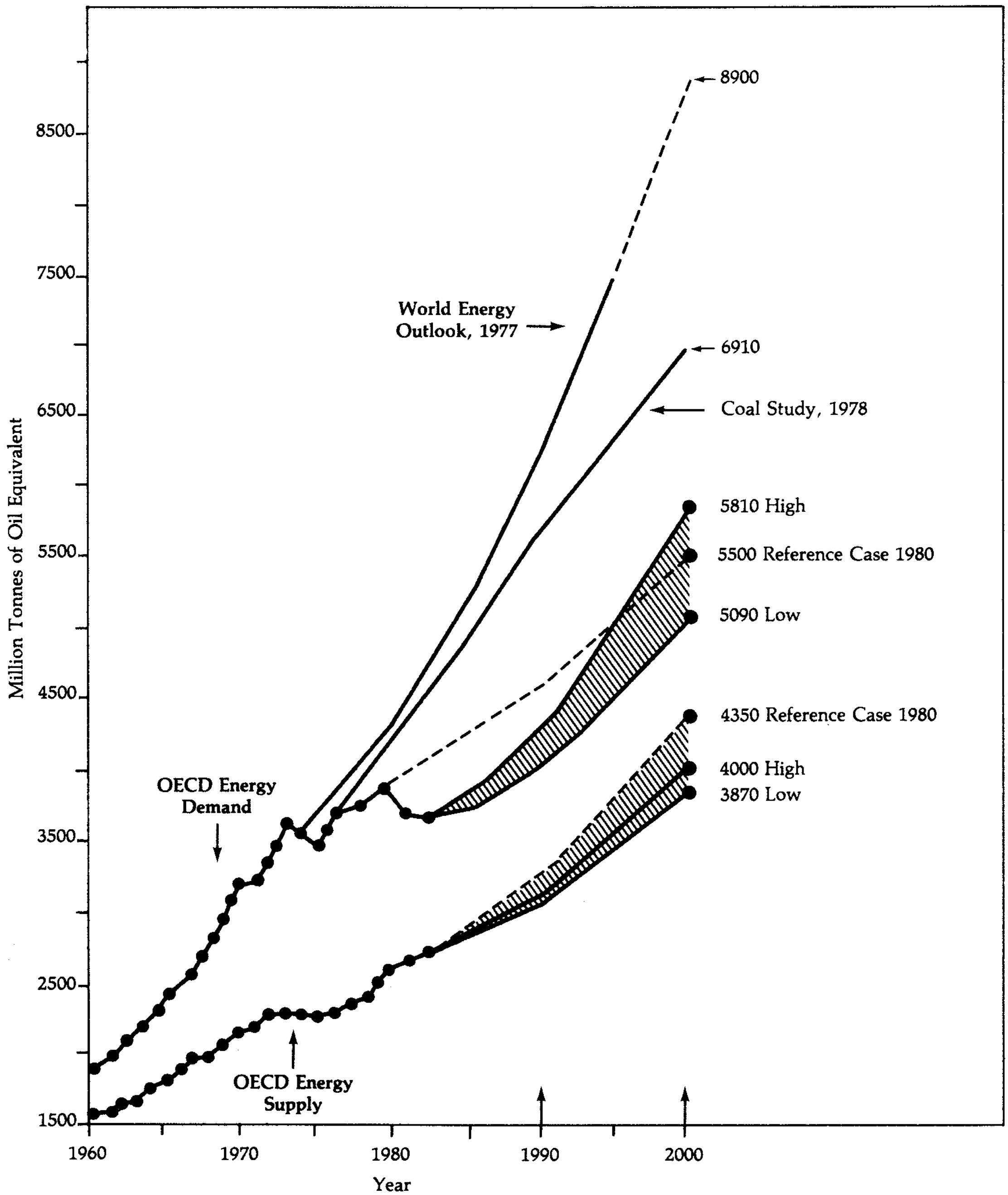
The energy price shocks of the 1970s prompted a number of institutions, both national and international, and scientists to project future energy demand and supply. In most of these projections, the energy future is portrayed as an extension of the past: energy demand is seen to rise steeply, so that virtually all energy supplies must be expanded at formidable rates to meet projected demand. Most have underestimated the potential of measures to increase energy efficiency, probably because the world had never before experienced anything remotely like the changes relating to energy that have occurred since the first oil shock.

What is striking about these efforts is that as time passed, the demand projections came down. For example, the International Energy Agency's demand projections dropped markedly between 1977 and 1980. *(See Figure 12.)* Energy demand projections for the United States also moved steadily downward. *(See Figure 13.)* The first effort exploring the prospects for energy efficiency improvement was the Ford Foundation's Energy Policy Project (EPP). In its final report, published in 1974, EPP suggested that "zero energy growth" for the United States was a possibility near the turn of the century, so that by the year 2000 demand would be "only" about 100 quads (quadrillion British thermal units [Btu]) per year.[11] This suggestion was roundly criticized at the time as "fuzzyheaded," "irresponsible," and "totally impractical" by a number of experts, including several on the project's board of advisors. In fact, it was then virtually impossible to find any energy analyst outside the Energy Policy Project who thought U.S. energy demand could be as low as 100 quads per year in the year 2000. Government agencies and the trade associations for the oil and gas, electric utility, and nuclear power industries were projecting energy demands of 150 to 170 quads by 2000. It was not long, however, before the Ford Project's middle-of-the-road "technical fix" scenario of 125 quads was adopted by energy analysts as conventional wisdom. The United States has already experienced zero energy growth for the period 1973 to 1985, and today most forecasters project a U.S. energy demand in 2000 of only 85 to 90 quads per year.

Why did analysts err on the high side? The most serious problem with these projections is that most were based on the assumption that in the future there would be a close coupling between a nation's energy demand and its level of economic activity, as measured by its GDP or gross national product (GNP). This correlation was indeed strong historically, but no more in the market-oriented industrialized countries. As we have already noted, a remarkable decoupling of energy and economic growth has already been seen for the OECD countries since 1973. *(See Figure 14.)*

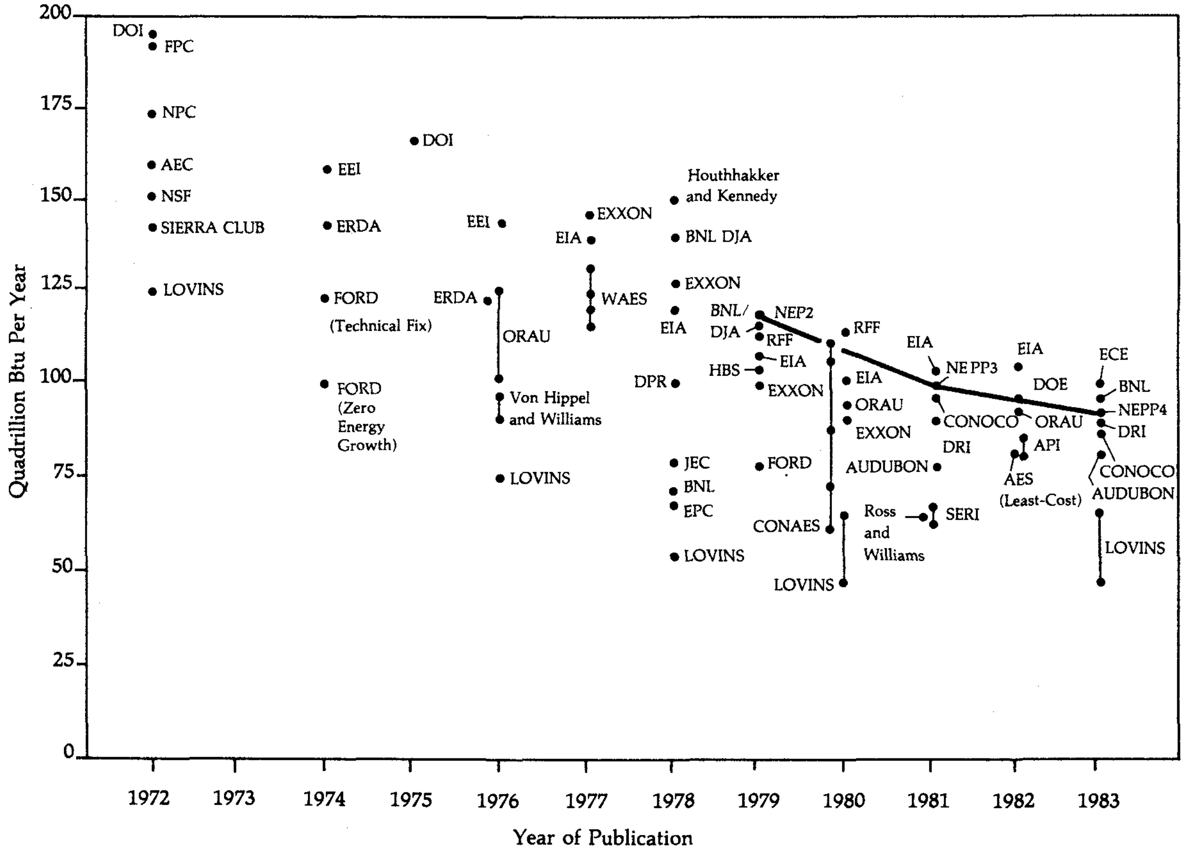
Certainly the most ambitious analysis of the global energy problem in this period, published

Figure 12. OECD Primary Energy Demand and Supply, History and Projections



The alternative projections were made in 1977, 1978, and 1980 by the International Energy Agency (*World Energy Outlook* [Paris: 1982]).

Figure 13. Forecasts of United States Primary Energy Requirements for the Year 2000 Versus the Years the Forecasts Were Made



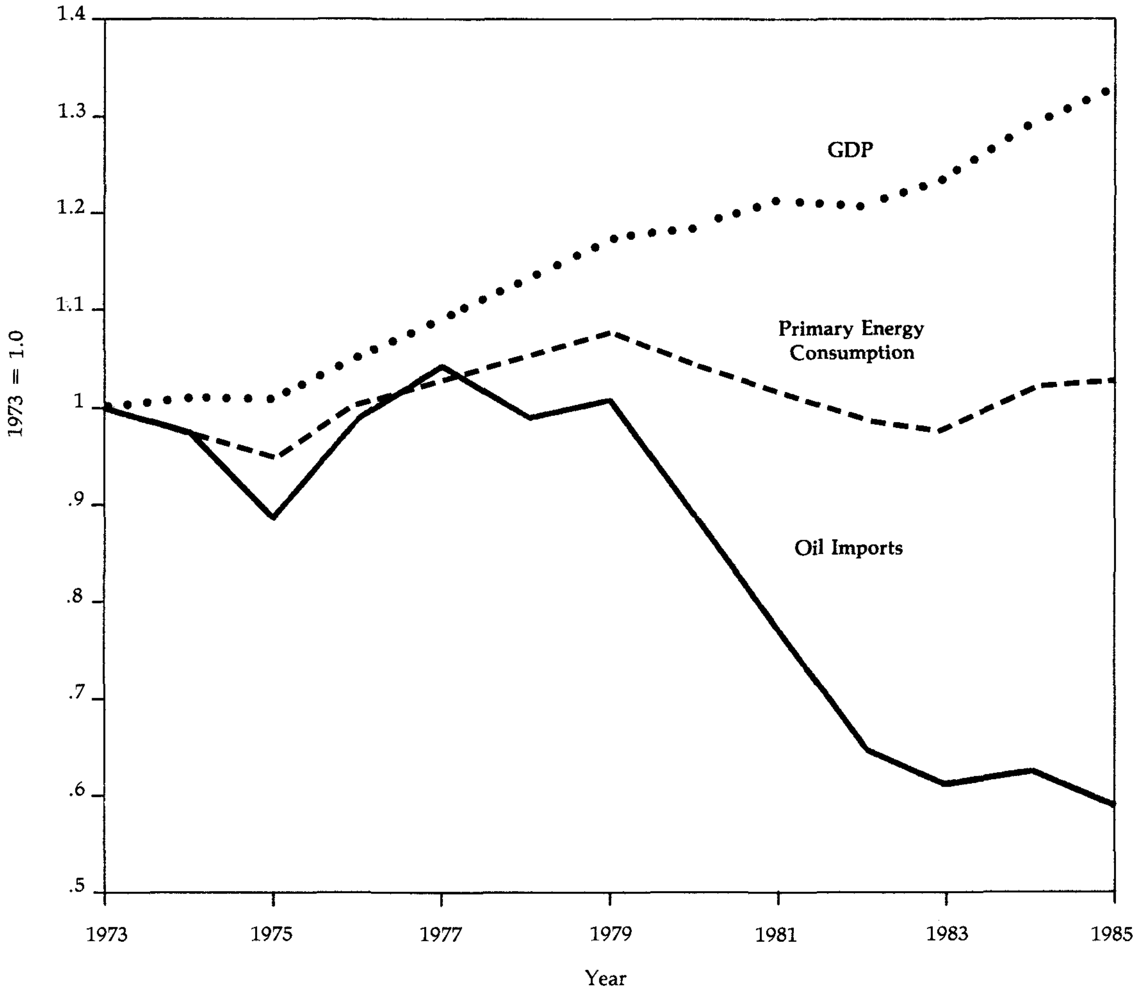
Source: U.S. Department of Energy, Office of Policy, Planning, and Analysis, "Energy Projections to the Year 2010: A Technical Report in Support of the National Energy Policy Plan," (Washington, D.C., October 1983).

in 1981, was carried out between 1973 and 1979 at the International Institute for Applied Systems Analysis (IIASA) by 140 scientists from 20 countries.[12] Another important study was published in 1983 by the World Energy Conference (WEC), the result of a cooperative effort of one central team and ten regional working teams involving 50 participants with diverse experience.[13] Less academic than the IIASA study, the WEC study gives a view of the energy future shared by most planners at energy companies and agencies and associated institutions. Both studies represent what might be called the conventional wisdom about energy at the time they were carried out. Their projections of global energy demand and supply for the year 2020 differ markedly from our own. *(See Figures 9 and 11.)*

The IIASA/WEC Numbers and Our Numbers: What They Mean

Future Energy Demand. The IIASA and WEC analysts generated high- and low-energy demand scenarios for the year 2020. In their low

Figure 14. Primary Energy Consumption, Net Oil Imports, and Gross Domestic Product for Organisation for Economic Co-operation and Development Countries, Relative to the Values of These Quantities in 1973



Source: For Energy Data: *BP Statistical Review of World Energy* (London: June 1986). For Gross Domestic Product Data: Organisation for Economic Co-operation and Development, *National Accounts of OECD Countries*, vol. I (Paris: 1985).

demand scenarios, global energy use would nearly double between 1980 and 2020; in their high-demand scenarios, it would increase 2.5 to nearly 3 times. For comparison, global energy use would be only 11.2 TW in 2020 according to our scenario, up only slightly from 10.3 TW in 1980. *(See Figure 9.)*

The IIASA and WEC scenarios involve no reduction in the great regional disparities in present energy use. In 2020, per capita energy use in industrialized countries would, according to both, be at least six times that in developing countries, just as it is today. Putting aside for the moment any consideration of the analytical basis for these projections, such strong growth in energy demand by the industrialized countries implies significantly higher world energy prices. The energy appetites of the industrialized countries would thus exacerbate a problem that is already frustrating development in developing countries and would certainly lead to intolerable North-South tensions.

Economic growth can, however, continue in the North without putting such pressures on world energy resources. Analysis based on detailed studies for Sweden and the United States indicates that per capita energy use could be reduced roughly by half in industrialized countries between 1980 and 2020 while per capita GDP grows by perhaps 50 to 100 percent. This decoupling of energy and economic growth reflects both an ongoing structural shift away from energy-intensive economic activities and the exploitation of opportunities for more efficient energy use. Thus, energy use by the industrialized countries could decline by 3 TW, from 1980 to 2020.

For developing countries, our scenario shows in the year 2020 a per capita primary energy use rate of 1.3 kW. Because of the expected near doubling of population, this implies that the developing countries' share of world energy use would increase from one third (its present value) to two thirds in 2020. Our demand projection is between the values given in the IIASA and WEC low and high scenarios, but developing countries could achieve a relatively better living standard with our scenario than this comparison indicates. In fact, any living standard up to that of Western Europe in the mid-1970s could be obtained with about the same per capita energy use as that prevailing today in developing countries. This result is achieved by shifting from traditional, inefficiently used *non-commercial* (biomass) fuels, which currently account for more than 40 percent of developing countries' energy use, *to such modern energy forms* as electricity, liquid and gaseous fuels, and processed solid fuels and by emphasizing efficiency improvements in energy-using equipment as economic development proceeds. With our scenario, the costs of providing energy services would be less than with more conventional supply-oriented development strategies, thus freeing up economic resources for other development.

Future Energy Supplies. Meeting the global demand levels projected in the IIASA and WEC scenarios would require monumental efforts to expand energy supplies. Consider the IIASA scenarios, which specify supplies of 19 to 28 TW of energy in 2020. *(See Figure 11.)*

To provide for both net growth and the replacement of retired facilities, the IIASA scenarios would require, for example, the opening of one new large nuclear power plant (1 gigawatt electric, GW(e)) every four to six days from 1980 to 2020. It would also require bringing on line new fossil-fuel production capacity equivalent to that of the Alaska pipeline—the equivalent of 2 mbd of oil every one to two months throughout this period. Such an enormous expansion in energy supplies would be exceedingly costly in terms of global security and the environment, as well as in terms of direct economic costs. The impacts of this development are made more vivid by examining each of the major supplies in turn.

Consider oil. To meet IIASA's demand levels, the Middle East and North Africa would have to produce at or near maximum capacity—34 mbd, compared to the average of less than 15 mbd produced from 1983 to 1985. This extent of dependence on Middle East producers would certainly put the OPEC cartel back in control of world oil prices, and oil importers could expect prices probably even higher than those demanded by the cartel in the 1970s. In addition, this dependence would create a volatile political situation. Military intervention in the area by the United States or its allies, sparked perhaps by a supply interruption aimed at diminishing U.S. support of Israel, would become much more likely. A superpower confrontation or even a major war might ensue. In short, the Middle East could become a nuclear flashpoint.

Under our projection, dependence on Middle East and North African oil could probably be sustained at the 1983–1985 "world oil glut" level of 15 mbd. Global oil demand would probably be so low that oil supplies available outside the Middle East and North Africa at production costs of less than $30 a barrel would be adequate to make up the difference between total demand and 15 mbd. The result would be both a lower world oil price than in the IIASA scenarios and greatly enhanced global security.

Next consider nuclear power. To meet IIASA's projected demand levels, installed nuclear generating capacity would have to increase to between 2,200 and 3,700 GW(e) by 2020, up from 120 GW(e) in 1980. With this amount of nuclear capacity, each year 2.1 to 3.5 million kilograms of plutonium would be recovered from spent reactor fuel and circulated in nuclear commerce around the world. However well meaning the international effort to prevent nuclear weapons proliferation, it is difficult to imagine how international institutions could adequately safeguard virtually all this material against occasional diversion by either terrorists or governments. It takes only 5 to 10 kilograms to make a nuclear weapon.

In our scenario, nuclear power is considered an energy source of last resort. Installed nuclear capacity would increase to only 460 GW(e) by 2020. No net increase in nuclear power beyond that already planned for the year 2000 would be necessary. The only nuclear plants built after the turn of the century would be those replacing retired plants. Under these circumstances, the economics of spent fuel recovery, nuclear fuel reprocessing, and plutonium recycling would remain unfavorable for the entire period and far beyond.

Now consider fossil fuels generally. Overall fossil fuel use would increase substantially with the IIASA scenarios, and coal use in particular would increase by 2 to 3.5 times. *(See Figure 11.)* The carbon dioxide (CO_2) content of the atmosphere would double by the second half of the next century, and major changes in the global climate would be likely well before then.

In our scenario, fossil fuel use would not increase, coal use would be reduced about 20 percent, and atmospheric CO_2 would be 1.3 times the pre-industrial level by 2020. If all remaining recoverable oil and natural gas were eventually used up, and if coal use were to continue declining at the rate of 0.6 percent per year (the rate of decline for the period 1980 through 2020 in our scenario), the level of carbon dioxide in the atmosphere would eventually reach 1.7 times the pre-industrial level.

The reduced use of oil and coal in our scenario would be offset by an increase in the use of natural gas, to the point at which oil and gas uses are equal. *(See Figure 11.)* A shift to natural gas would help reduce the CO_2 problem because the combustion of natural gas releases only about half as much CO_2 per unit of energy as does coal combustion. Because oil prices, and thus natural gas prices, would not rise much in our low-demand scenario, natural gas would be preferred to coal, which, when used in environmentally acceptable ways, entails large capital investments.

The shift to natural gas also makes sense from the perspective of resource availability. There is probably about as much recoverable gas left in the ground as there is oil. Yet, natural gas is used at only about half the rate of oil.

Our low-demand scenario would certainly not solve the CO_2 problem. An eventual atmospheric CO_2 level 1.7 times the pre-industrial level would still induce significant climatic change. Our scenario would buy time however. If acceptable long-term alternatives to fossil fuels are not developed, there would be much more time to adjust to a changed global climate than if the IIASA or WEC projections were realized. It is more likely that acceptable alternative fuel sources (such as hydrogen produced from amorphous silicon cells[14]) will become available in the next few decades, making it feasible to phase out fossil fuels more quickly.

A More Hopeful Outlook

Fortunately, energy futures such as those described by the IIASA and WEC analyses are not inevitable. It turns out that the world needs less energy, much less, than most energy analysts thought in the 1970s and early 1980s. To meet the energy needs of the world's 7 billion citizens in 2020 would not require doubling or tripling present energy requirements by 2020; roughly as much energy as we now use would be enough *if* energy planners worried less about supply expansion and much more about efficiency improvements at the point of energy use.

The world needs less energy, much less, than most energy analysts thought in the 1970s and early 1980s.

We have not shown that the global energy balances we have arrived at are consistent with what can be achieved in a particular region or country; that important exercise remains to be carried out. But our analysis does suggest that there are no obvious significant global constraints to an energy future consistent with the solutions to other important global problems. Our analysis also stops short of identifying a truly sustainable long-run energy future; we have not looked beyond the year 2020. Before then, however, new technology will make long-range problems even more manageable. Meanwhile, energy planners should not strive to solve the energy problem for all time, but, rather, they should pursue an evolutionary energy strategy consistent with the achievement of a sustainable world.

IV. Behind the Numbers

Energy is only one important global problem that must be managed in the decades ahead if a sustainable world society is to be achieved. Other pressing problems include the global economic crisis, North-South tensions, widespread poverty in developing countries, population growth, food scarcity, the risk of nuclear war, nuclear weapons proliferation, environmental degradation, the human role in global climate change, and deforestation and desertification. As the preceding discussion shows, all these problems are strongly related to energy use.

The global energy strategy pursued should be consistent with efforts to solve these other global problems. In other words, it should contribute to achieving such social goals as economic efficiency, equity, environmental soundness, human welfare, and peace. But most studies of the global energy problem have not focussed on these links to other important global problems. Rather the implicit assumption in most analyses is that the energy future is largely determined or is restricted to a relatively narrow range of outcomes, with little room for changes people may induce. Using models that tightly couple economic growth with growth in energy use, most global energy analyses thus project large increases in future energy requirements and then focus on the efforts needed to expand energy supplies to satisfy projected energy needs. In these analyses, the consequent global risks of overdependence on Middle East oil, fossil fuels generally, and nuclear power are either ignored or regarded as the necessary price of progress.

In addition, the energy problems of developing countries are usually slighted in most global energy analyses. The burdens of having to compete for scarcer, more costly energy supplies because of industrialized countries' growing energy appetite are usually ignored. Moreover, though nearly half the energy consumed by the three fourths of humanity living in developing countries is non-commercial energy,[15] non-commercial energy has not been an important consideration in most global energy analyses. To the extent that developing countries are considered, their energy futures are typically decribed as following the path already taken by industrialized countries.

Any global energy strategy pursued should contribute to achieving such social goals as economic efficiency, equity, environmental soundness, human welfare, and peace.

A New Approach

Our analysis focusses on end uses rather than aggregate energy consumption. Because the use of energy is not an end in itself, we have not studied the use of energy in the traditional way, using "macro descriptors" of aggregate energy demand—e.g., the income and price elasticities economists use to explain energy-consumption behavior. Obviously, energy is useful only insofar as it provides such services as cooking, lighting, heating, refrigeration, mechanical work, and personal and freight transport in ways that improve the quality of life. Accordingly, we have tried to understand the role of energy in society better by scrutinizing the patterns of energy end uses—asking how and by whom different forms of energy are used today and how the energy end-use system might look in the future. Using this end-use approach, we explore the feasibility of modifying the evolution of the energy system in ways that would facilitate or be compatible with the achievement of a sustainable society.

We have identified possible energy features far outside the range normally considered in long-term energy projections. *(See Figures 9 and 11.)* The end-use approach helps identify problems (e.g., whether progress is being made in eradicating poverty), trends (e.g., structural shifts in the economy), and new possibilities (e.g., more energy-efficient end-use technologies) that are obscured in energy analyses based on highly aggregated descriptors.

If total energy demand is not too great, planners have flexibility in charting the energy course to meet overall energy needs at acceptable costs, to reallocate resources to fulfill unmet social needs, and to select a mix of energy supplies that avoids or minimizes dependence on the most troublesome sources. Significant flexibility in energy planning has already been achieved by OECD countries, where there has been no increase in energy use since 1973, despite a large increase in economic output. *(See Figure 14.)* We focus on the potential for further decoupling energy use and economic growth, in both industrialized and developing countries, and on the resulting flexibility to pursue energy strategies consistent with achieving a sustainable world society.

Structural Shifts in Industrialized Market-Oriented Countries

The economies of market-oriented industrialized countries are undergoing structural changes that are reshaping their energy demands. These economies have entered the post-industrial phase of economic growth, in which the service sector grows rapidly relative to the goods-producing sector while the manufacture of goods shifts to products characterized by a high ratio of value added to material content. Both these trends are leading to a less energy-intensive mix of economic activity.

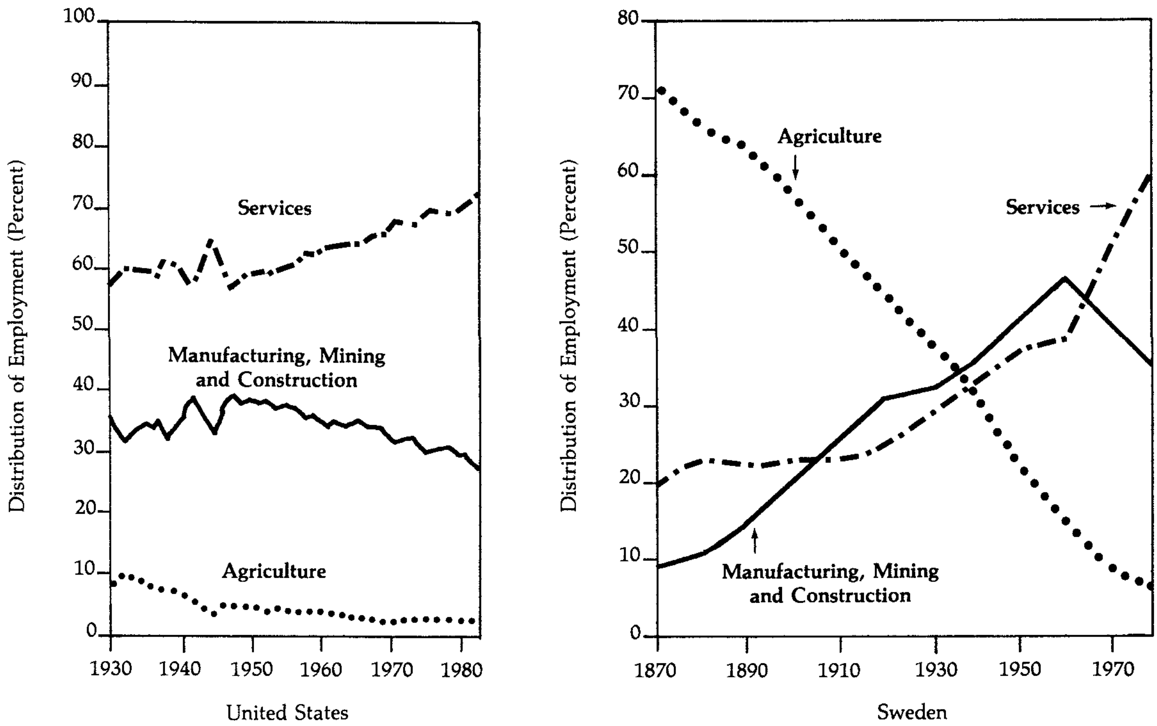
Growth of the Service Sector. The role of services—in finance, insurance, information management, marketing, medical care, and education, for example—relative to the production of goods has been increasing for decades in industrialized market economies. This change is reflected in the long-term employment trends of Sweden and the United States. *(See Figure 15.)*

In the early years of industrialization, the shares of employment accounted for by manufacturing and services both grew while employment in agriculture declined. Mechanization of agriculture made it possible for the production of food and fiber to increase at the same time. Over the last few decades, the service sector has been growing relative to manufacturing as well. This trend is significant because providing services generally requires much less energy per dollar of output than manufacturing goods does.

The shift to services is also reflected in the economic output of the goods-producing sector. In the United States, goods production (measured by the value-added index of "gross product originating") grew just 0.83 times as fast as GNP between 1960 and 1980. In Sweden, it grew 0.6 times as fast.

The Growing Importance of Fabrication and Finishing. A more recent development relating to goods production is that the demand for a

Figure 15. Sectoral Distribution of Employment in the United States (Left) and Sweden (Right)



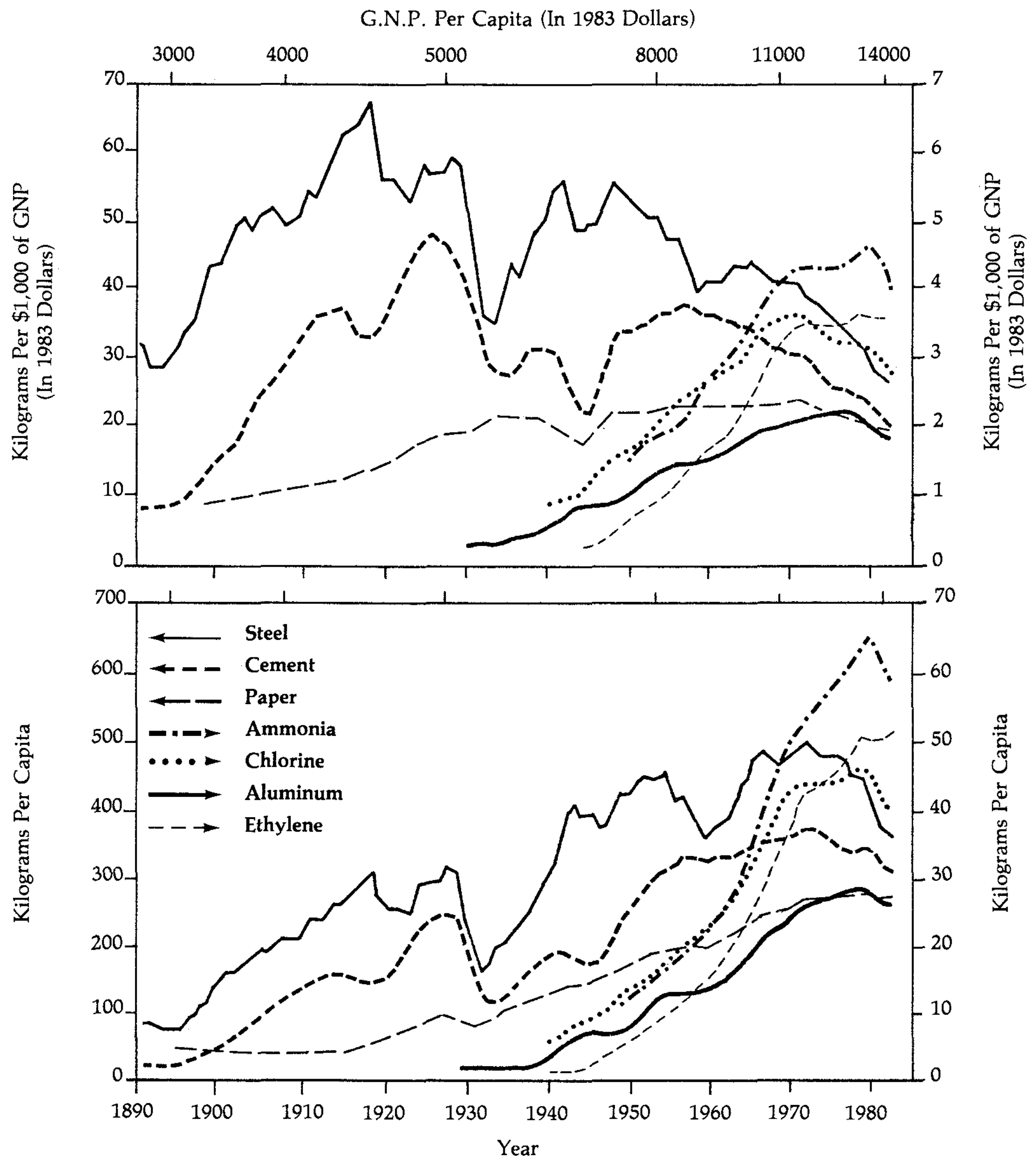
For the United States, the employment measure is the number of full-time equivalent employees. For Sweden it is the number of employees working more than half time.

wide range of materials, both traditional and modern, is no longer increasing in physical terms (measured in kilograms per capita per year). *(See Figure 16, bottom, and Figure 17.)*

For traditional materials, this recent development can be explained in part by the substitution of more modern materials. In addition, both traditional and modern materials are being used much more efficiently—for example, through the development of higher strength or more durable products. The high-strength steel girders used recently to repair the Eiffel Tower weighed just one third as much as those replaced. Although inter-material competition and the increased cost of materials have accelerated improvements in the efficiency of materials use, this trend is not a new phenomenon—witness the continual drop in the weight-to-power ratio for locomotives from the beginning of the 19th Century to the present. *(See Figure 18.)*

Although materials substitution and increased efficiency of materials use are clearly contributing to the shift away from basic materials, today these factors are probably not as important in reducing demand as the saturation of markets for bulk materials and heavy consumer goods and a shifting of consumer preferences to products characterized by a higher ratio of value added to material content. Today the af-

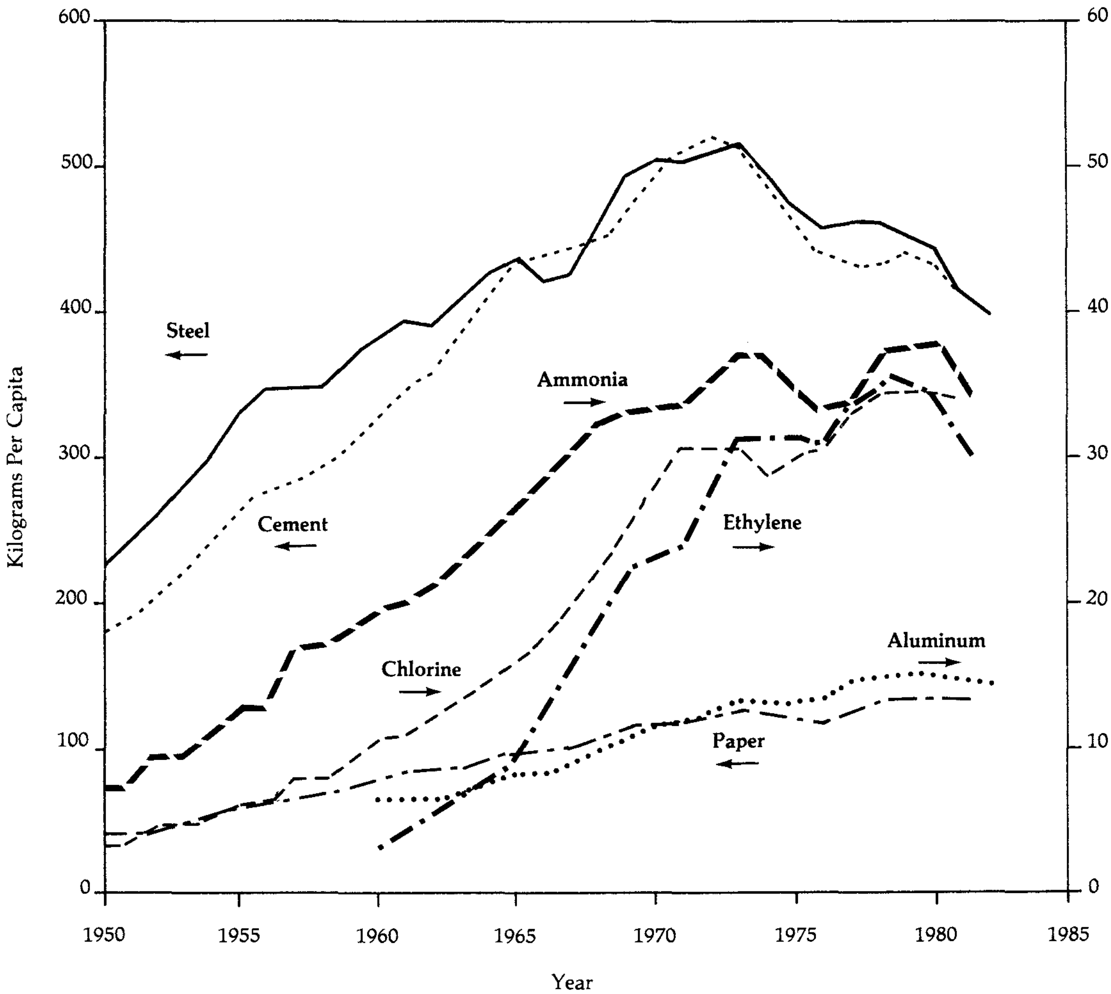
Figure 16. Trends in Consumption Per Capita (Bottom) and Consumption Per Dollar of Gross National Product (Top) in the United States for Both Traditional (Steel, Cement, Paper) and Modern (Aluminum, Ethylene, Chlorine, and Ammonia) Basic Materials



The data are for apparent consumption (production plus net imports, adjusted for stock changes), and the plotted points are for 5-year running averages.

Source: R.H. Williams, E.D. Larson, and M.H. Ross, "Materials, Affluence, and Industrial Energy Use," *The Annual Review of Energy 12* (1987): 99-144.

Figure 17. Trends in the Apparent Consumption Per Capita for Selected Basic Materials in Western Europe

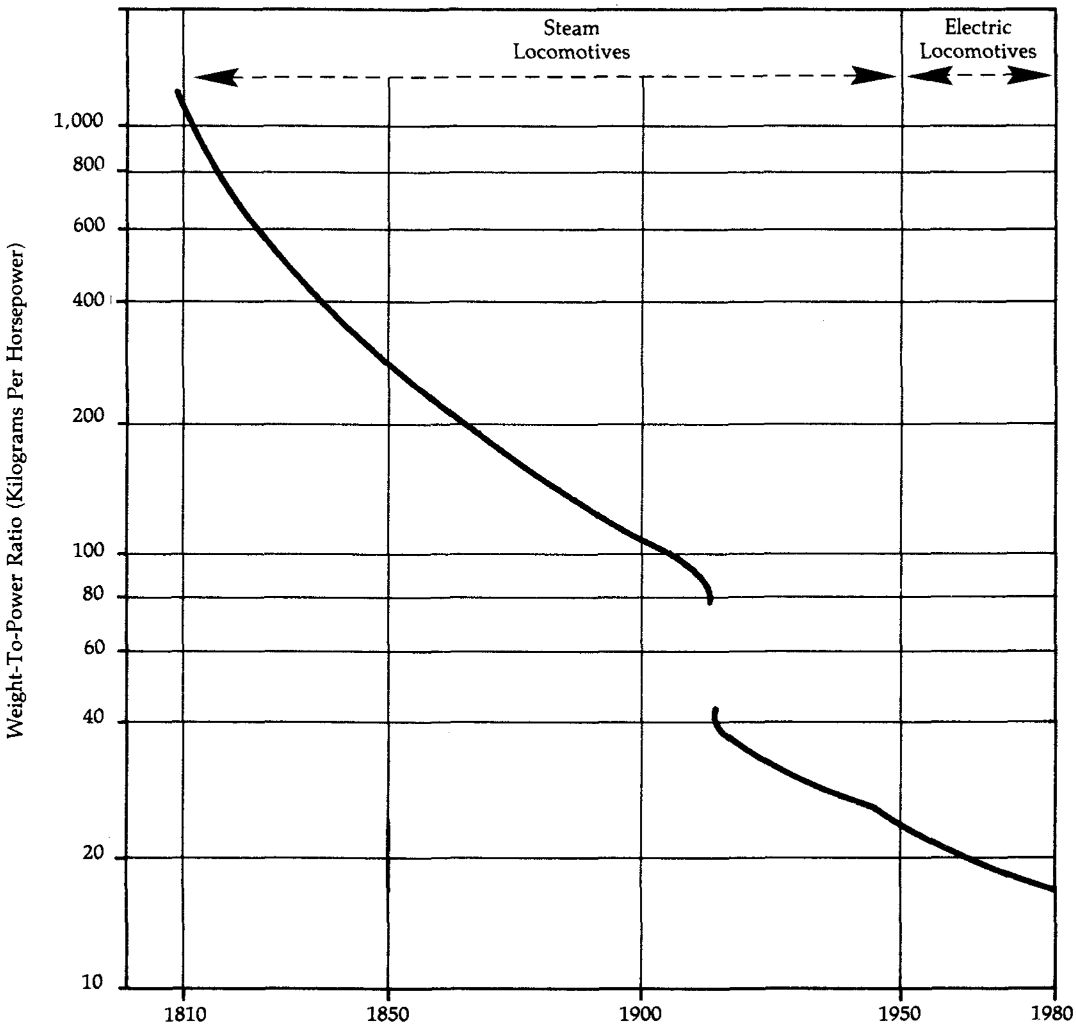


The data shown are aggregates of apparent consumption for the Federal Republic of Germany, France, and the United Kingdom. The ammonia data are for the Federal Republic of Germany and France only. The plotted points are 3-year running averages.

Source: M. Ross, E.D. Larson, and R.H. Williams, "Energy Demand and Materials Flow in the Economy," *Energy, the International Journal,* in press.

fluent tend to spend additional income not on extra refrigerators or cars but on such items as video cassette recorders and personal computers and software. Moreover, even in replacement markets, the trend is toward reduced material intensity. As more affluent consumers replace their old appliances and automobiles with more expensive new ones, they are buying products

Figure 18. Trends in the Weight-to-Power Ratio of Locomotives Between 1810 and 1980



The weight-to-power ratio for locomotives decreased nearly 70-fold between 1810 and 1980 as a result of improvements in design and materials. In the mid-19th Century iron was replaced by steel in boilers—a change that made possible lighter equipment and higher internal pressures. Between 1810 and 1900 the ratio declined 10-fold, and it declined another 4-fold by 1950, when the electric locomotive was introduced. (The gap between 1910 and 1920 results from the disruption of data collection during World War I.)

Similar (albeit less dramatic) improvements have been made in many industrial products. Substitution and design changes that lead to more efficient use of materials are two of the factors responsible for the leveling off of demand for basic materials in the industrialized market economies.

Source: Economic Commission for Europe, *Evolution of the Specific Consumption of Steel* (New York: United Nations, 1984).

containing less material per dollar of price. The downward trend in material intensity with price is illustrated for a wide range of traditional consumer products in Sweden. *(See Figure 19.)*

These changing consumer preferences are reflected in a production shift away from processing basic materials to fabricating and finishing increasingly complex goods that are characterized by low ratios of material content per dollar of value added (e.g., high-strength and corrosion-resistant steels and specialty chemicals for the fast-growing pharmaceutical, electronics, and biotechnology markets).

The high-strength steel girders used recently to repair the Eiffel Tower weighed just one third as much as those replaced.

The concept of the life cycle of a material in the economy can be helpful in understanding recent trends in materials use in industrialized countries. At the beginning of this cycle, when a material is first introduced, consumption rates are low and there are vast potential markets. In this phase, consumption grows rapidly—usually much more rapidly than the overall economy. This growth encourages advances in processing technology that generally increase productivity, leading to lower prices and improved product quality, thus stimulating further growth in demand. In the next phase of the cycle, the ratio of value added to the kilogram content of material increases as more sophisticated products are emphasized. In this phase, the demand for the material measured in kilograms of material per dollar of GNP peaks and begins to decline. Such was the situation in the steel and cement industries in the United States in the 1920s and 1930s and in Sweden in the 1950s and 1960s. *(See Figure 16, top, and Figure 20.)* This trend also occurred in the late 1970s in the United States for important modern materials—ammonia, ethylene, chlorine, and aluminum. *(See Figure 16, top.)*

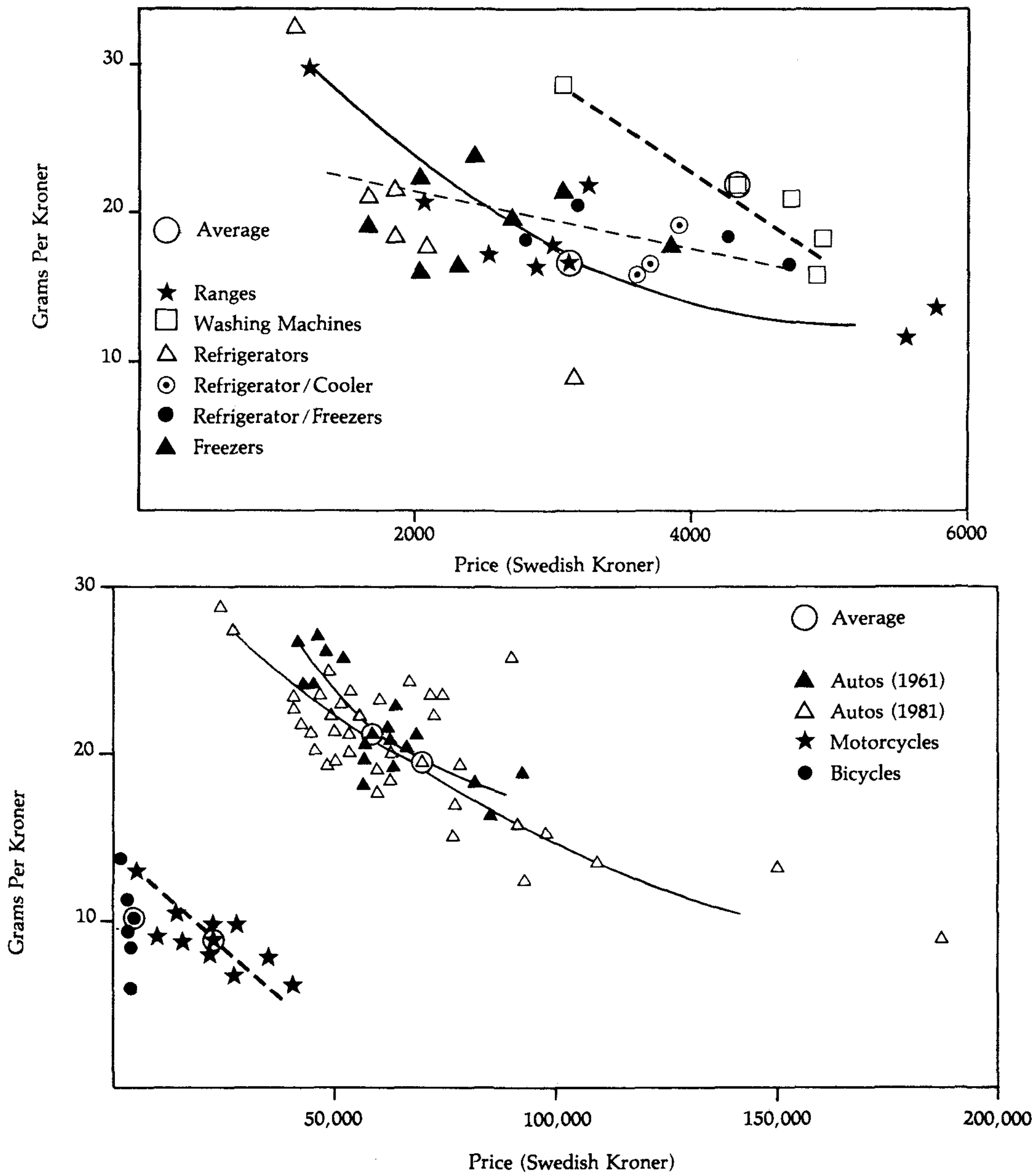
Materials use per capita often continues to grow after materials use per dollar of GNP begins to decline. (Compare the top and bottom curves in Figure 16.) Eventually, however, materials-intensive markets approach saturation, and new markets are largely for specialty products that have little effect on total consumption. In this stage, per capita consumption levels off and may even begin to decline, as is now happening in the United States and Western Europe. *(See Figure 16, bottom and Figure 17.)*

The energy demand implications of this shift away from basic materials are profound. The industries that process basic materials (petroleum refining; primary metals; paper and pulp; chemicals; stone, clay, and glass; and food processing) account for most energy use in manufacturing, while the fabrication and finishing industries (the rest of manufacturing) account for most value added. These latter industries require only a tiny fraction of the energy required in processing basic materials per dollar of value added. *(See Figures 21 and 22.)* This shift therefore implies a substantial decoupling of industrial energy use from industrial output. In the United States, the shift away from basic materials accounted for an average annual reduction of 1.6 percent in the ratio of industrial energy use to GNP between 1973 and 1985.[16] If this structural shift had not occurred, industrial energy demand in 1985 would have been higher by the equivalent of 3.2 million barrels of oil per day, or roughly three fourths of all oil imports that year.

The Structure of Energy Demand in Developing Countries

In contrast to industrialized countries, for many years most developing countries will need to expand materials-and energy-intensive

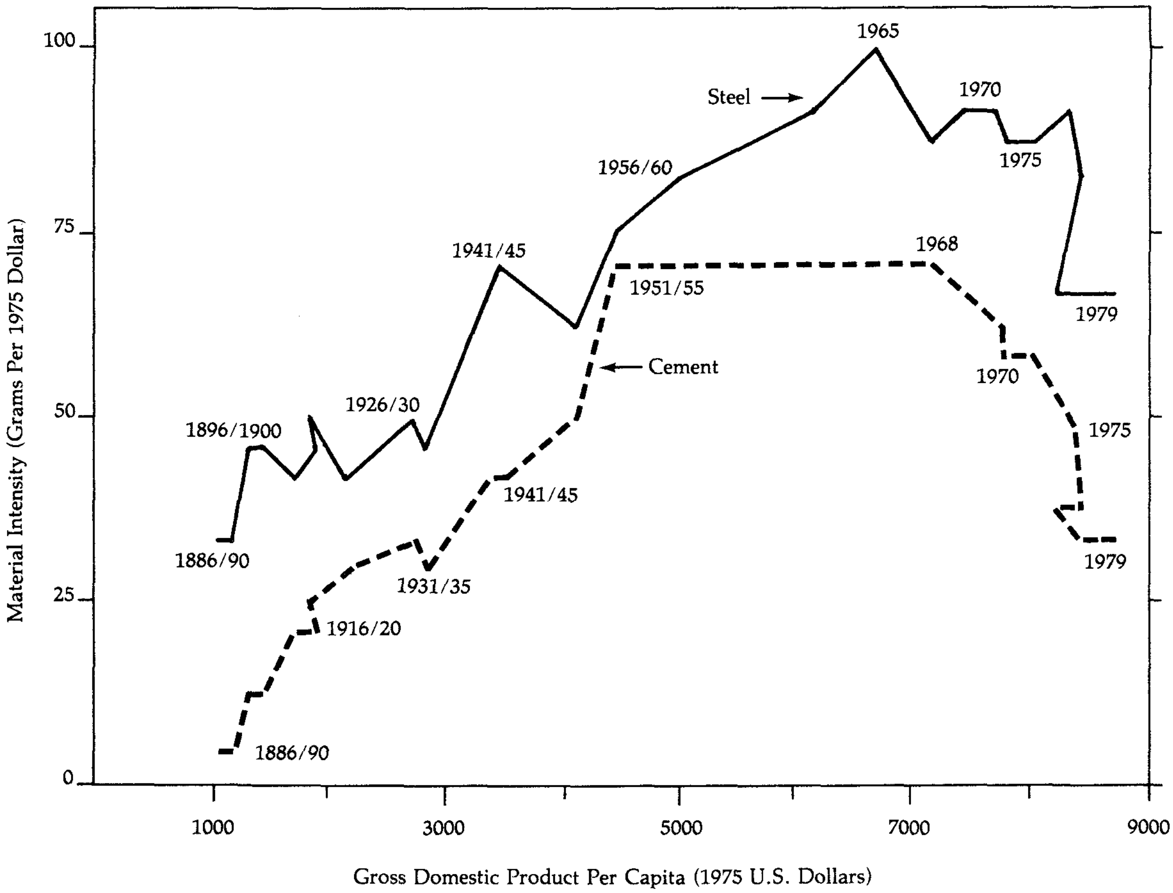
Figure 19. Material Intensity for Household Appliances (Top) and Transport Vehicles (Bottom) Versus Sales Price in Sweden



The downward trend of the materials intensity with increasing sales price shows that as their incomes increase and they purchase more costly products, consumers tend to buy less materials-intensive (more value added-intensive) products.

Source: T.B. Johansson and P. Steen, *Perspectives on Energy* (Stockholm: Liber Vorlag, 1985). In Swedish.

Figure 20. The Material Intensity of Steel and Cement in the Swedish Economy Versus Standard of Living Over Time in Sweden



Source: P. Steen, *et al.*, *Energy—For What and How Much?* (Stockholm: Liber Vorlag, 1981). In Swedish.

economic activities—building and operating more factories, schools, hospitals, office buildings, houses, and transport systems and manufacturing consumer products for domestic markets that are far from saturated.

The energy required for this development can vary significantly, however, according to the development strategy selected. The development strategy underlying our analysis emphasizes the satisfaction of basic human needs, industrial activities that promote new employment, and agricultural production.

Energy and Basic Human Needs. In the 1950s, it was widely believed that maximizing economic growth was the best way to eradicate poverty. However, the benefits of rapid economic growth have not trickled down to the poor. While rapid growth is necessary for successful development, it is not sufficient. A more effective way of fighting poverty is by directly allocating resources, including energy, to meet basic human needs for nutrition, shelter, clothing, health, and education.[17] There is no empirical evidence showing that targeting basic human needs slows economic growth.[18] In fact, theory suggests that satisfying such needs would speed growth because farmer and worker productivity would increase.[19]

If the emphasis in development is on satisfying basic human needs, the societal patterns of energy use, the kinds of energy-using equipment deployed, and the kinds and amounts of supplies produced are all affected. In a needs-based energy strategy, for example, the wide use of fuel-efficient cooking stoves would be promoted, both for those who can purchase them and for those living outside the market economy, who cannot afford them. Taking this approach would reduce the increasing drudgery of gathering and hauling wood, drudgery borne primarily by women and children. It would also ease pressure on wood resources and perhaps help end their unsustainable exploitation. In addition, it might free some fuelwood resources for rural industrialization and other uses.

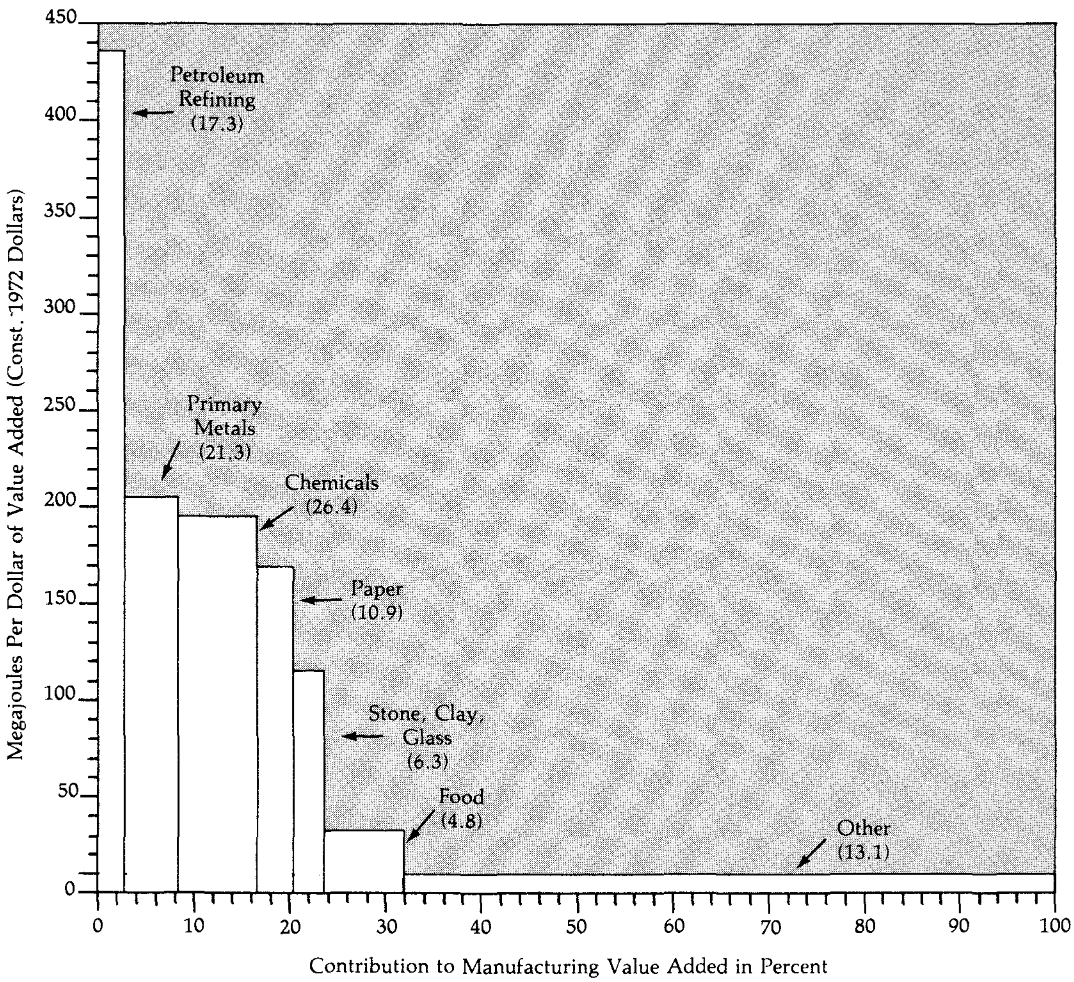
The industries that process basic materials account for most energy use in manufacturing, while the fabrication and finishing industries account for most value added.

Emphasizing efficient stoves would require major new efforts to manufacture, market, and distribute the stoves to the general population. Such a program would be ambitious, but it could provide many benefits while using only a fraction of the financial resources required by conventional attempts to expand energy supply. An annual investment of $1 billion would provide efficient fuelwood stoves to all the 400 million rural households of developing countries (assuming that each stove costs $5 and lasts two years on average). Much fuelwood would be saved—enough, for example, to produce electricity in biomass-fired power plants equal to the output of about 80 large nuclear power plants costing $160 billion.

Emphasizing basic needs would also mean trying to electrify every household. Today, even in countries with rural electrification programs, typically only 10 to 15 percent of rural households are electrified. Reaching all households often requires greater emphasis on decentralized electricity production (for example, producer-gas engine generator sets for villages) because centralized electricity production is simply uneconomical or impractical for many rural needs. A society that emphasizes basic needs would also seek to bring clean water and good sanitation to every household, requiring a pattern of direct and indirect energy use quite different from the one that emerges when production is geared to satisfying elite consumers.

More generally, a society determined to meet basic needs would develop the capacity to produce a wide range of goods and services for the domestic population. In turn, emphasizing mass domestic markets requires industrial development with a mix of materials-intensive basic industries and fabrication and finishing industries to convert the processed raw materials into industrial and consumer products. Such an economy would be, on average, less energy-intensive than one that emphasizes the export of processed basic materials such as steel, aluminum ingot, and basic chemicals because fabrication and finishing activities in developing countries are far less energy-intensive than the basic materials processing industries, just as they are in industrialized countries. *(See Figures 21, 22, and 23.)*

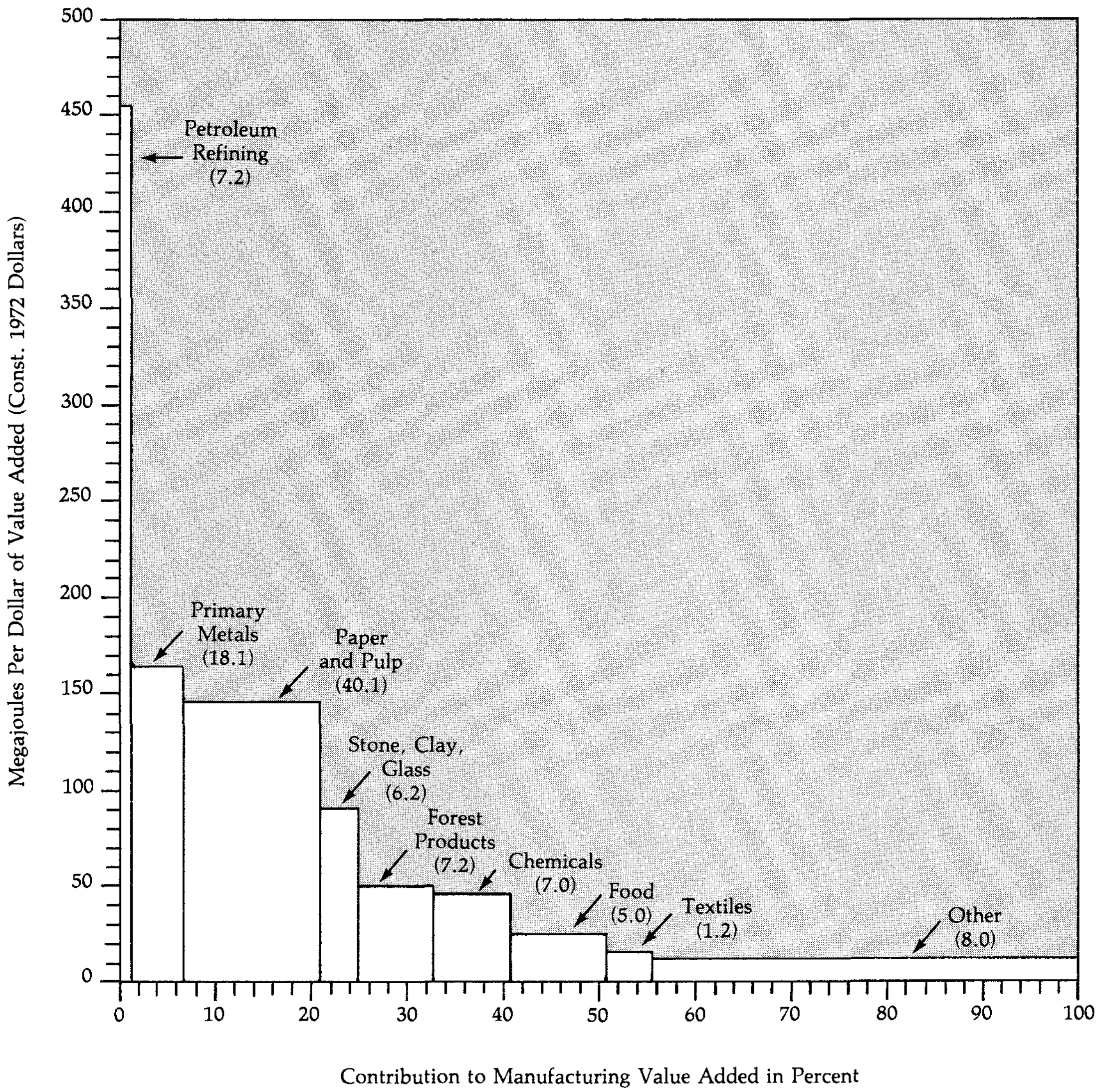
Figure 21. Final Energy Intensity Versus Manufacturing Value Added for United States Manufacturing Industries in 1978



The number displayed for each bar is that sector's contribution (in percent) to total final energy use in United States manufacturing.

Energy and Employment Generation. The unemployment now rife in developing countries must be a foremost concern in any development strategy. Unemployment is so serious largely because many current production technologies are ill-suited to developing countries' needs. While developing countries are capital-poor and labor-rich, many available technologies are capital-intensive and labor-saving, designed primarily for industrialized countries. Of course, the labor-intensive technologies used in Europe and North America during their industrialization in the 19th Century would not be competitive today, partly because

Figure 22. Final Energy Intensity Versus Manufacturing Value-Added for Swedish Manufacturing Industries in 1978.

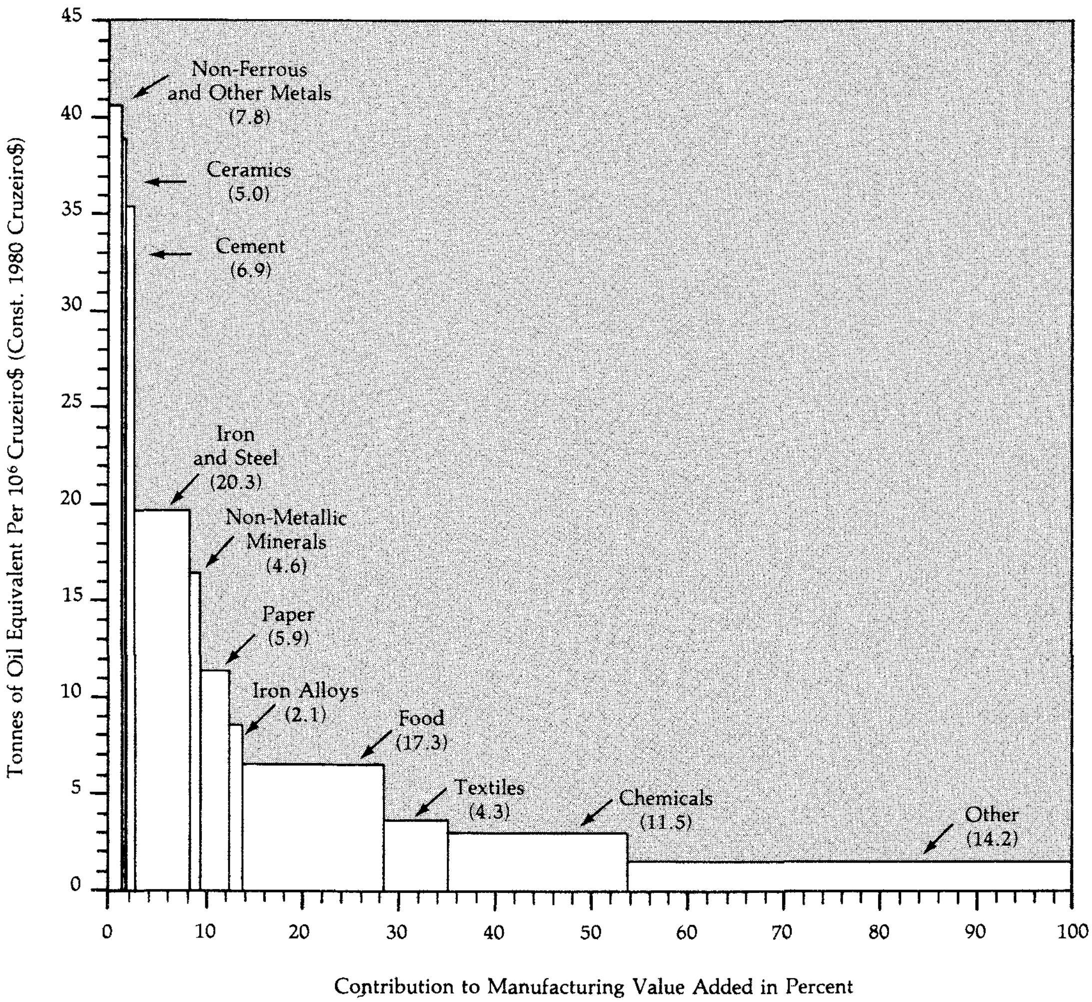


The number displayed for each bar is that sector's contribution to total final energy use in Swedish manufacturing, in percent.

they are too energy-intensive for today's energy prices. But the employment implications of alternative technologies and strategies for industrialization must be taken into account.

Gainful employment provides the purchasing power that enables people to satisfy some of their basic needs. In rural areas, the lack of such employment not only keeps per capita in-

Figure 23. Final Energy Intensity Versus Manufacturing Value Added for Brazilian Manufacturing Industries in 1980



The number displayed for each bar is that sector's contribution (in percent) to total final energy use in Brazilian manufacturing.

come extremely low but also induces people to migrate to already overburdened cities.

Of course, some industries generate far more jobs than others. Most basic materials processing industries have both low labor intensities and high energy intensities, the fabrication and finishing industries have high labor intensities and low energy intensities. In the industrial sector of the state of Karnataka in India, for example, 18 electro-metallurgical firms consumed two thirds of all industrial electricity and directly employed 4,000 people. In contrast, 1,200 other firms used the remaining one third of industrial electricity but provided employment for 250,000.[20]

Naturally, developing countries cannot base development exclusively on fabrication and finishing industries. Yet, planners should guard against over-investment in industries with low employment potential. For this reason, investments in basic industries aimed at export markets should be approached cautiously. If, instead, basic industries are expanded largely to serve domestic markets and are complemented by new fabrication and finishing industries, many more jobs would be created and much less energy would be required. Moreover, when manufactured exports are required to earn foreign exchange, much more value would be added and employment created if finished materials instead of processed basic materials (for example, aluminum-intensive automobiles instead of aluminum ingot) were exported.

Energy supply choices can also significantly affect unemployment. In particular, it takes far more labor to plant, grow, harvest, and process biomass for energy production than to produce fossil fuels. The Brazilian alcohol program, which produced about 11 billion liters of ethanol from sugar cane in 1985, illustrates the point. The program requires an investment of only $6,000 to $28,000 per job, compared to the average of $42,000 for Brazilian industry and $200,000 per job for the oil-refining/petrochemical complex at Camarcari. In 1985, the ethanol program directly generated an estimated 475,000 full-time jobs in agriculture and industry, along with another 100,000 jobs indirectly in commerce, services, and government.[21]

Brazil's ethanol program is also cost-effective. The cost of producing this ethanol has been estimated at $50 to $56 (in 1983 U.S. dollars) per barrel of gasoline replaced when the subsidies are removed and a realistic exchange rate based on the parity value of exported goods is used.[22] This cost is competitive with gasoline produced in Brazil from imported crude oil at the 1981 world oil price, a price that will likely be reached again in the next decade. The ethanol program has also dramatically reduced oil imports and associated foreign exchange requirements, displacing 55 percent of the gasoline that would otherwise have been demanded in 1985.

Among biomass's other appeals as an energy source are its wide availability in rural areas and its suitability for conversion to useful energy in relatively small-scale systems. Both features facilitate rural industrialization, which in turn creates jobs where they are most needed.

Energy for Agriculture. A major challenge for developing countries in the decades ahead is to feed rapidly growing populations. To meet this challenge, the United Nations Food and Agriculture Organization (FAO) has called for modernizing traditional agriculture so as to double agricultural production by the year 2000.[23]

An important concern in modernizing agriculture is the implications of such change for employment. Traditional low-yield agriculture is labor-intensive, and modern, mechanized, energy-intensive, high-yield agriculture is not—or so goes the conventional wisdom. Some analysts thus worry that in many developing countries modernization will exacerbate unemployment or underemployment and will further increase inequities in income. After all, countries that have already passed from agrarian to industrial economies have watched their agricultural work forces shrink. On the other hand, if agricultural output is increased using traditional labor- and land-intensive methods, agricultural production will demand more forest and marginal lands, aggravating the already serious deforestation and desertification.

Comparing modern and traditional agricultural techniques in this way may be simplistic, however. Agricultural modernization is not simply a "black box" through which capital, energy, and other inputs can be substituted for labor to increase yield per hectare.[24] Rather, many different technological possibilities exist for modernizing various aspects of agricultural production. Increased energy and capital inputs do not necessarily reduce labor inputs or increase crop output. The outcome depends on what combination of technologies is used, as has been shown for rain-fed rice culture, which accounts for half the Asian rice production and yielded 411 million tonnes in 1982. *(See Figure 24.)* The pumping of water for irrigation in dry periods is a good example of how increased use of energy can promote employment generation. Multiple cropping is then possible, and multiple cropping increases labor requirements.

Agricultural modernization is not simply a "black box" through which capital, energy, and other inputs can be substituted for labor to increase yield per hectare.

Although modernizing agriculture need not entail job losses, it does require extra energy for mechanical tillers, tractors, irrigation pumps, fertilizer production, and other means of crop production. According to FAO, meeting this goal would require increasing the commercial energy used for agriculture at an average annual rate of 8 percent, from the equivalent of 0.74 million barrels of oil per day in 1980 to 3.5 mbd in 2000.[25] Despite the high growth rate, however, the amount of extra energy required is not large in absolute terms. Indeed, the increment required between 1980 and 2000, about 2.8 mbd, is no more than the amount of oil the United States saved between 1978 and 1981. Providing this much extra energy for agriculture need not be particularly burdensome—for example, in terms of foreign exchange requirements for oil-importing countries. In fact, agriculture's increased requirements could be satisfied largely through energy-efficiency improvements in major oil-using sectors such as transportation. *(See Table 4.)*

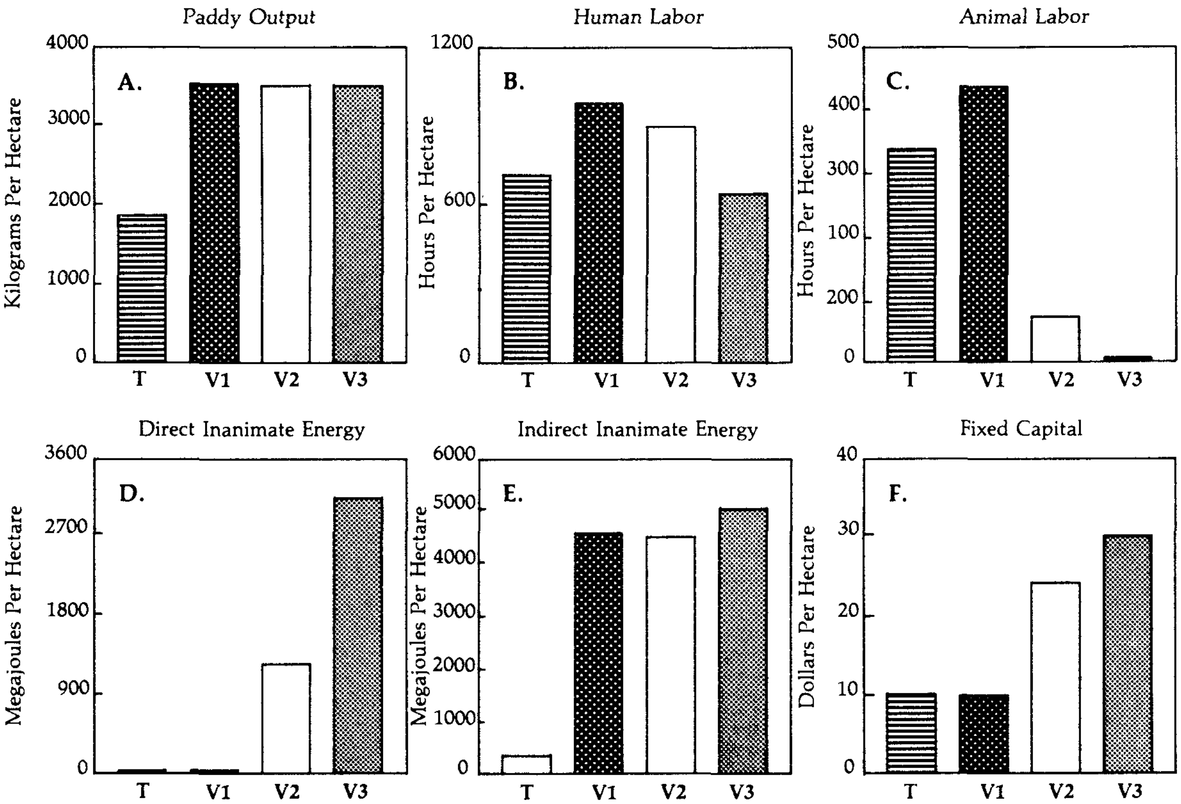
There are also alternatives to petroleum for meeting agriculture's energy requirements. Agriculture's energy demands could provide developing countries an incentive to develop synthetic fuels from biomass, such as methanol derived by thermochemical processes from organic residues or wood. Methanol in an amount equivalent to 2.8 mbd of oil could be produced with 50-percent overall conversion efficiency, using 40 percent of the organic wastes—crop residues, animal manure, and food-processing wastes—generated in developing countries today. Alternatively, methanol could be produced from wood from trees grown on energy plantations. At an annual yield of 10 tonnes per hectare, roughly 66 million hectares—about 3 percent of the forested area in developing countries—would be required to meet agriculture's increased energy requirements. Clearly, the availability of energy need not constrain the production increases FAO projects.

Energy Planning as an Instrument of Development. Instead of simply retracing the development path once traveled by the industrialized countries, developing countries must chart new courses reflecting their unique resource capabilities and constraints. Although development goals cannot be achieved by energy planning alone, our analysis has shown that energy planning can be a powerful instrument of development, in light of the central role of energy—in meeting basic human needs, in generating employment, and in meeting agricultural goals.

Opportunities for Using Commercial Energy More Efficiently

The economies of both industrialized and developing countries present abundant opportunities for making commercial energy use more efficient. It usually costs less to save a unit of energy through more efficient use than

Figure 24. Paddy Output, Human Labor, Animal Labor, Direct and Indirect Inanimate Energy, and Fixed Capital Costs of Selected Technologies for Rice Production



T = **Traditional Technology:** No hybrid seeds, chemical fertilizer, pesticides, or herbicides; no use of oil for transport vehicles or land preparation. Instead traditional seed varieties and organic fertilizers are used, with draught animals used for land preparation, manual transplanting, and manual harvesting, threshing, and winnowing.

V1 = **Variant 1:** Differs from Traditional Technology in that it uses modern biological-chemical inputs (hybrid seeds, fertilizer, insecticides, and herbicides).

V2 = **Variant 2:** Differs from Variant 1 by using tractors for plowing and mechanical driven vehicles for transport while retaining draught animals for harrowing.

V3 = **Variant 3:** Uses power threshers and replaces the tractors of Variant 2 with power tillers ("walking tractors") for plowing and harrowing.

Source: A.K.N. Reddy, "The Energy and Economic Implications of Agricultural Technologies: An Approach Based on the Technical Options for the Operations of Crop Production," PU/CEES 182 (Center for Energy and Environmental Studies, [Princeton University, Princeton, New Jersey, 1985]): and ILO World Employment Programme Research Working Paper 2-22/WP 149 (Geneva: International Labor Organization, June 1985).

Table 4. Distribution of Petroleum Consumption by End Use (in Percent)

	Ethiopia, 1979	India, 1978
Agriculture	5.5	13.8
Industry	12.3	6.5
Transport	64.7	55.3
Household	0.7	20.3
Commercial	3.0	
Mining	0.5	
Road Construction	5.3	4.1
Electricity Production	5.6	
Other	2.4	
	100	100

Sources: For Ethiopia: R. Hosier, et al., "Energy Planning in Developing Countries: Blunt Axe in a Forest of Problems?" *Ambio,* vol. 11, no. 4(1982): 180–187. For India: A.K.N. Reddy, "An End-Use Methodology for Development-Oriented Energy Planning in Developing Countries, with India as a Case Study," PU/CEES 181, Center for Energy and Environmental Studies, Princeton University, Princeton, New Jersey, 1985.

to produce an additional unit by expanding the energy supply. Four of the many areas that show promise for efficiency improvements are space heating, appliances, automobiles, and steelmaking.

Space Heating in Industrialized Countries. Space heating accounts for 60 to 80 percent of final energy use in residential buildings in industrialized countries. Prospects are good for cost-effectively reducing energy requirements for space heating to a minor fraction of household energy use by reducing heat losses and improving heating system efficiencies.

SHELL MODIFICATIONS IN NEW HOMES
Heat losses can be reduced by increasing insulation, by adding extra glass panes to windows, and by reducing natural air infiltration. Indoor air quality can be maintained in a tight house by replacing natural ventilation with mechanical ventilation and by using a heat exchanger to transfer heat from the stale exhaust air to incoming fresh air or to water for domestic heating.

A good measure of a house's energy performance is the heating system's energy output, adjusted for floor area and climate variations. In the United States and Sweden, improved energy performance has been demonstrated in various groups of new houses incorporating energy-saving features. *(See Table 5.)* Enormous improvements compared to both the existing housing stock and to typical new construction are possible in both countries. New superinsulated houses, such as the Northern Energy Home (NEH) marketed in New England, have extremely low energy requirements. *(See Figure 3.)* A NEH in the New York City area with 120 square meters of floor space could be heated with electric resistance heaters for just 1,400 kWh per year, roughly the same amount of electricity that a typical new refrigerator-freezer consumes.

Table 5. Space Heat Requirements in Single Family Dwellings (kJ per square meter per degree-day)[a]

United States	
Average, housing stock	160
New (1980) construction	100
Mean measured value for 97 houses in Minnesota's Energy Efficient Housing Demonstration Program	51
Mean measured value for 9 houses built in Eugene, Oregon	48
Calculated value for a Northern Energy Home in New York City area[b]	15
Sweden	
Average, housing stock[c]	135
Homes built to conform to the 1975 Swedish Building Code[d]	65
Mean measured value for 39 houses built in Skane[e]	36
Measured value, house of Mats Wolgast[f]	18
Calculated value for alternative versions of the prefabricated house sold by Faluhus[g]	
Version No. 1	83
Version No. 2	17

Sources: For U.S. housing stock average: R.H. Williams, G.S. Dutt, and H.S. Geller, "Future Energy Savings in US Housing," *Annual Review of Energy* 8(1983): 269–332. For new U.S. construction and nine houses in Oregon: J.C. Ribot et al., "Monitored Low-Energy Houses in North America and Europe," in *What Works: Documenting Energy Conservation in Buildings,* J. Harris and C. Blumstein, eds., proceedings of the Second Summer Study on Energy Efficient Buildings (Washington, D.C.: American Council for an Energy Efficient Economy, 1983), 242–256.

a. The required output of the space heating system per unit floor area per heating degree day (base 18° C).
b. The Northern Energy Home (NEH) is a superinsulated home design based on modular construction techniques with factory-built wall and ceiling sections mounted on a post and beam frame. The energy performance was estimated using the CIRA computer program (personal communication from D. Macmillan of the American Council for an Energy Efficient Economy, Washington, D.C.). The house has 120 square meters of floor area, triple-glazed windows with night shutters, 20 centimeters (23 cm) of polystyrene insulation in the walls (ceiling), 0.15 air changes per hour (ACH) natural ventilation plus 0.35 ACH forced ventilation via 70 percent efficient air-to-air heat exchanger, and an internal heat load of 0.65 kilowatts. The indoor temperature is assumed to be 21° C in the daytime, set back to 18° C at night.
c. In 1980 the average values for fuel consumption, floor area, and heating degree days were 98.5 gigajoules, 120 square meters, and 4,474 degree days, respectively, for oil heated single family dwellings. For conversion of fuel use to net heating requirements, a furnace efficiency of 66 percent is assumed (L. Schipper, "Residential Energy Use and Conservation in Sweden," *Energy and Buildings,* vol. 6, no. 1(1984): 15–38.).
d. For a single story house with 130 square meters floor area, no basement, electric resistance heat, an indoor temperature of 21° C, and 4,010 degree-days.

Table 5. Continued

e. The average for 39 identical 4 bedroom, semi-detached houses (112 square meters of floor area, 3,300 degree-days).
f. The Wolgast house has 130 square meters of heated floor space, 27 centimeters (45 cm) of mineral wool insulation in the walls (ceiling), quadruple glazing, low natural ventilation plus forced ventilation via air preheated in ground channels. Heat from the exhaust air is recovered via a heat exchanger. For 3,800 degree-days.
g. The Faluhus has a floor area of 112 square meters. The more energy-efficient Version No. 2 (with extra insulation and heat recuperation) costs 3,970 SEK (US $516) per square meter compared to 3,750 SEK (U.S. $488) per square meter for Version No. 1. The annual electricity savings for the more efficient house would be 8960 kWh per year. The cost of saved energy (assuming a 6 percent discount rate and a 30-year life for the extra investment) would be 0.20 SEK per kilowatt hour (U.S. $0.026 per kilowatt hour). For comparison electricity rates for residential consumers in Sweden consist of a fixed cost independent of consumption level of about 1,200 SEK (U.S. $156) per year plus a variable cost of 0.25 SEK (U.S. $0.032) per kilowatt hour.

Although the costs of improved energy performance in new construction vary significantly from builder to builder, the cost of saved energy is generally less than the cost of purchased heating fuel or electricity. *(See Box 3.)* Surprisingly, growing evidence indicates that the net extra cost of even superinsulated houses may not be very large compared to the cost of conventional houses. Consider two versions of a Faluhus prefabricated house in Sweden that are identical except for their energy use characteristics and first costs. *(See Table 5.)* For the more efficient version, one of the most energy-efficient houses built, the cost of saved energy is still less than the cost of electricity in Sweden at current rates, even though these rates (based largely on hydropower) are very low—far below marginal costs.

The economics of improving energy efficiency may actually be even more favorable than such calculations suggest, because the additional investment brings several benefits—such as increased comfort or reduced maintenance requirements. Superinsulated houses generally are not drafty. And the efficient version of the Faluhus uses a forced ventilation system that filters incoming air.

HEATING SYSTEMS FOR NEW HOMES The noteworthy achievements in reducing heat loss through superinsulated house designs have been matched in recent years by improvements in the design of furnaces and heat pumps. Manufacturers in Europe and North America are marketing high-efficiency natural gas and oil furnaces that use one third less fuel than conventional furnaces do. Even though these furnaces typically cost $600 to $700 more than other new furnaces, they are cost-effective in the United States wherever the heating requirements exceed half the average for the existing housing stock.[26]

In superinsulated houses, though, these high-efficiency furnaces would be cost-effective at present prices only in very cold climates—for example, in Canada, Sweden, or in the New England, Upper Midwest, and Northern Rocky Mountain regions of the United States. For superinsulated houses in moderate climates, where space heating is needed only on the coldest days, a different approach is possible: it is feasible to heat with a few small wall-mounted space heaters. These heaters would be far less costly than a central furnace and heat-distribution system, thus offsetting much of the extra cost of the superinsulated building shell. In such houses, the internal temperature variation is less than in ordinary houses with conventional heating systems.

With new high-performance heat pumps, substantial energy savings are possible in electrically heated houses. In 1982, the most efficient unit available in the United States provided 2.6 units of heat per unit of electricity consumed, that is, its coefficient of performance (COP) is 2.6.[27] This unit requires one third less electricity than the typical heat pumps in use, which have a COP of about 1.7.

Most heat pumps sold in the United States extract heat from outside air. In very cold weather such heat pumps perform no better than resistance heaters. Good performance is possible in cold weather, though, with heat pumps that extract heat from warmer sources. An ingenious system employed in new Swedish housing extracts heat from the warm exhaust air in air-tight, mechanically ventilated houses and uses it mainly to preheat domestic hot water. A very high COP of 3 is achieved by such systems, which are cost-effective even in Sweden's well-insulated houses. A COP of 3 is also achieved with large district-heating heat pumps in Sweden that draw heat from sewage, lake, or sea water.

SHELL MODIFICATIONS FOR EXISTING HOUSES Improving the thermal performance of existing houses is crucial because they will dominate the industrialized countries' housing stock for many decades.

Thermal design improvements are generally more costly for existing houses than for new ones, and some housing features cannot be modified easily. Yet numerous cost-effective ways of improving energy performance are widely available today for existing houses. They include insulation, storm windows, clock thermostats, and various retrofits for the heating system. Even so, these conventional measures do not exhaust the possibilities.

Box 3. Economic Figures of Merit

In this study, three figures of merit are used to assess the cost-effectiveness of energy-saving investments: the cost of saved energy, the life-cycle cost, and the internal rate of return.

The cost of saved energy is an index having energy price units that permits a ready comparison between investments in energy efficiency and energy supply alternatives. Simply stated, the cost of saved energy is the annual repayment on a hypothetical loan taken out to pay for an investment to save energy, divided by the expected annual energy savings. Both principal and interest charges (corrected for inflation) are included, and the term of the loan is equal to the expected life of the investment. An investment in energy efficiency is cost-justified if the cost of saved energy is less than the cost of the energy supply alternative being considered.

The life-cycle cost is the present value of all costs associated with providing a particular energy service, with future costs discounted to present worth using an inflation-corrected market rate of interest. A comparison of the life-cycle costs for different energy systems provides a simple means of identifying the least costly energy strategy.

The internal rate of return is the real (inflation-corrected) rate of return realized from the dollar value of the energy savings resulting from an energy-saving investment. The decision rules with this index are that: (1) to be considered cost-justified, the internal rate of return for an investment must be greater than some threshold "hurdle rate" that represents the opportunity cost of capital and (2) the investment offering the highest rate of return would be favored.

Detailed measurements in the late 1970s revealed that obscure defects in houses' thermal envelopes allow far greater heat losses than were predicted by traditional heat-loss models. Fortunately, auditing procedures aided by instruments such as house pressurization devices and infrared viewers now permit these defects to be identified quickly.[28] Such audits are much more costly than walk-through, non-instrumented audits that many U.S. gas and electric utilities offer. However, many of the obscure defects discovered with instruments can be corrected on-the-spot with low-cost materials. When such improvements are made at the time of the audit, the costly diagnostic procedure becomes a very cost-effective way to save significant amounts of energy, even in houses with attic and wall insulation and storm windows.

This "house doctor" concept was tested in the Modular Retrofit Experiment by gas utilities in New Jersey and New York in collaboration with the Buildings Research Group at Princeton University. In this experiment, a one-day, two-person house doctor visit saved, on average, 19 percent of the gas use associated with space heating.[29] Later conventional shell-modification retrofits brought the total fuel savings to an average of 30 percent, for an average total investment of about $1,300. The real rate of return on this investment, in fuel costs savings, was nearly 20 percent.[30]

The achievements demonstrated commercially in the Modular Retrofit Experiment do not represent all that can be done through shell improvements in existing dwellings. One reason is that energy-saving shell improvements become more cost-effective when they are accompanied by home improvements made for reasons other than energy savings. For example, if old windows are replaced to reduce drafts, facilitate cleaning, or make a room more pleasant, energy-saving windows are economically attractive compared to conventional replacement windows, even when replacement windows cannot be justified on the basis of the expected energy savings alone. Over the years, there will be many opportunities to incorporate new energy-saving features this way in typical houses.

A second reason is that new technologies for energy savings will continually be commercialized. One experiment by Princeton University researchers suggests the possibilities. These researchers exploited unconventional retrofit opportunities that brought about energy savings of two thirds in a house regarded as "thermally tight" by U.S. standards *before* it was modified.[31]

HEATING SYSTEMS FOR EXISTING HOUSES The economics of efficient furnaces or heat pumps tend to be much better in the replacement market than in new housing because the heat loads in the former are relatively large. Even after major shell improvements, heating requirements greatly exceed those in new superinsulated houses. For example, if new energy-efficient condensing gas furnaces were introduced after the shell improvements were made in the houses of the Modular Retrofit Experiment, the fuel requirements for space heating could be reduced to 44 percent rather than only 70 percent of the pre-retrofit level. Installing a new condensing furnace instead of a new conventional furnace that costs $1,000 less would result in a 15-percent rate of return on the extra investment.[32]

Appliances in Industrialized and Developing Countries. Water heating accounts for between 10 and 35 percent of residential energy use in industrialized countries. In the United States and Sweden, refrigeration accounts for one fourth of residential electricity use. Lighting typically accounts for about half as much electricity use as refrigeration.

WATER HEATING Recently, gas-fired water heaters that use only half as much fuel as conventional units have become available, and the most efficient new heat-pump water heaters use only one third as much electricity as conventional electric resistance units do.[33]

REFRIGERATION Recent innovations in refrigeration technology have led to new refrigerators, refrigerator-freezers, and freezers that use far less electricity than units now in wide use. The most energy-efficient refrigerator-freezers on the market in Europe, Japan, and the United States, for example, require only 1.3 to 1.6 kWh per liter of cooled volume annually, compared to 3.5 kWh per liter for the average units (450 to 500 liters) now common in the United States. Still more efficient units are under development. *(See Table 6.)*

The cost of saved energy for the more efficient units now on the market is far less than the cost of electricity,[34] and the initial costs of more efficient units may fall as the new technology becomes commonplace. As with new houses, synergistic energy-saving strategies can help reduce first costs. For example, investments to reduce heat losses may be offset by the reduced costs of lower-capacity motors and compressors.

The wide use of energy-efficient refrigeration technology could significantly affect electricity supply requirements. For instance, if the existing U.S. stock of refrigerator-freezers were replaced by the most efficient models available commercially in 1982, the *energy saved would be equal to the output of about 18 large nuclear or coal power plants,* or the output of 18 GW(e) of baseload electrical generating capacity.

LIGHTING The incandescent bulb has dominated residential lighting since it was first introduced in 1879. The more efficient fluorescent lighting has not caught on for home use because most people prefer the soft yellow light of the incandescent bulb to the harsher white light of fluorescents. As noted earlier, though, new high-efficiency compact fluorescent lightbulbs are three to five times as efficient as incandescents, they last several times as long, and the newest do not have the drawbacks of the earliest models. *(See Figure 6.)* Although they cost far more than incandescents, these more efficient bulbs are cost-effective in many circumstances.

An indication of the overall possibilities for energy savings in the residental sector is provided by a comparison of the actual average energy use levels for the residential sectors of Sweden and the United States with the levels that would be realized in hypothetical superinsulated, all-electric houses having a full set of the most energy-efficient appliances now available commercially. Enjoying more amenities than the average household today, these hypothetical households would nevertheless use less than one fourth as much energy per capita as the average household. *(See Table 7.)*

APPLICATIONS IN DEVELOPING COUNTRIES Investments in energy efficiency may actually be more important for developing countries than for industrialized countries. This finding is contrary to the conventional wisdom that poor countries cannot afford to make the capital investments needed to improve the efficiency of energy use. Although more energy-efficient end-use devices do tend to be more costly than conventional units, the extra investment is typically much less than what would be required for an equivalent amount of energy supply expansion. Thus, investments in energy efficiency can lead to a net overall capital savings by society.

For example, compare the cost in Brazil of saving 1 kW by investing in efficient compact fluorescent light bulbs with the cost of the extra kW of hydroelectric supply that would be required if incandescent bulbs were used instead. *(See Figure 25.)* The cost in each case, as a function of the discount rate, is the discounted present value of all required investments over a 50-year life cycle.

At a 10-percent discount rate, the cost of expanding supplies per kW is about three times the cost of saving one kW by investing in more efficent bulbs. Moreover, the benefit of investing in energy-efficient bulbs actually increases as the discount rate rises. This savings occurs in part because the purchases of efficient light bulbs are spread over the life of the energy supply facility, so that the present value of

Table 6. Energy Performance of Refrigerators and Refrigerator-Freezers

Brand (Origin)	**Model**	**Type**	**Capacity** (liters)	**Specific Electricity Use**[a] (kilowatt hour per liter per year)	**Electricity Use**[a] (kilowatt hour per year)
Average, 45 U.S. Models	(1983)	1 door	363	1.94	703
Hitachi (Japan)	617A	1 door	169	1.36	230
Gram (Europe)	K215	1 door	215	1.26	270
Kenmore (United States)	564.86111	1 door	311	1.19	370
National (Japan)	211	1 door	207	0.99	205
Laden (Europe)	40.830	1 door	305	0.95	290
Bosch (Europe)	KS2680SR	1 door	255	0.86	220
Gram (Europe)	K395	1 door	395	0.80	315
Gram (Europe)	prototype[b]	1 door	200	0.52	104
Average, 488 U.S. Models	(1983)	2 door	518	2.46	1275
Bosch (Europe)	KS3180ZL	2 door	310	1.77	550
Amana (United States)	TSC18E	2 door	510	1.71	870
National (Japan)	291(HV/T)	2 door	290	1.65	480
Amana (United States)	ESR14E	2 door	402	1.58	635
Whirlpool (United States)		2 door	487	1.54	750
Electrolux (Europe)	TR1120C	2 door	315	1.51	475
Amana (United States)	prototype	2 door	510	1.43	730
Kelvinator (United States)	prototype	2 door	510	1.39	710
Toshiba (Japan)	GR411	2 door	411	1.31	540
Amana/Kelvinator	conceptual[c]	2 door	510	1.14	580
Pedersen	prototype[d]	2 door	510	0.94	480
Schlussler	prototype[e]	2 door	368	0.68	252

a. Electricity use values may not be directly comparable, because they are based on standardized tests that may vary from country to country.

b. Refrigerator with automatic defrost but no freezer. This prototype was designed and analyzed at the Physics Laboratory III, Technical University of Denmark, in cooperation with the refrigerator manufacturer Bdr. Gram A/S, Vojens, Denmark, and the compressor and control systems manufacturer Danfoss A/S, Norborg, Denmark (J.S. Norgard, J. Heeboll, and J. Holck, "Development of Energy-Efficient Electrical Household Appliances: Progress Rep. No. 4 for the Period Sept. 15 1982 to March 15, 1983," Technical University of Denmark, Lyngby, Denmark, 1983).

c. This requirement is the estimated consumption that would result from combining the efficient compressor utilized in the Kelvinator prototype with the other energy saving features of the Amana prototype [H.S. Geller, *Energy Efficient Appliances* (Washington, D.C.: American Council for an Energy Efficient Economy, 1983)].

Table 6. Continued

d. Frost-free unit designed for two California utilities (PG&E and SCE) at the Physics Laboratory III, Technical University of Denmark. The energy-saving features include: integrating the condenser into the inner side of the outer cabinet, to reduce the condenser temperature while simultaneously eliminating the need for anti-sweat heaters; using separate compressors for the refrigeration and freezing compartments; and increasing slightly the amount of insulation (P.H. Pedersen, "Reducing Electricity Consumption in American Type Combined Refrigerator/Freezer," in *Procedings of the 37th Annual International Appliance Technical Conference* (Lafayette, Indiana: Purdue University, Indiana, in press)).
e. Horizontal unit designed by Larry Schlussler at the University of California at Santa Barbara (L. Schlussler, "The Design and Construction of an Energy-Efficient Refrigerator," The Quantum Institute, University of California at Santa Barbara, June 1978).

these purchases declines rapidly with the discount rate. In addition, the total investment for energy supply expansion must be made before the new power plant is completed, and the accumulation of interest charges during construction causes the present value of the supply investment to rise with the discount rate. The difference between these two costs rises with the increasing discount rate, so that the societal benefit of the energy-saving bulbs looks better and better as the discount rate rises—a result that holds for a wide range of energy-saving investments.[35] Surprisingly, then, investments in energy efficiency improvement will often make even more sense in capital-short developing countries than in rich industrialized countries.

Investments in energy efficiency may be more important for developing countries than for industrialized countries.

Significant gains are possible from shifting to an energy strategy focussed on end uses. Analysis of opportunities for more efficient energy use throughout the electrical sector in Brazil has shown, for example, that investments totaling less than $10 billion over the period 1985-2000 in more efficient refrigerators, street lighting, lighting in commercial buildings, motors, and variable speed drives for industrial motors would eliminate the need to construct 22 GW(e) of electrical capacity costing some $44 billion.[36]

Investments in energy efficiency offer various benefits in addition to such direct economic benefits. For example, in southeastern Brazil, untapped hydroelectric resources are quite limited. When they are exhausted, much more costly thermal electric power plants will be needed. Improving the efficiency of electricity-using devices will delay this costly shift.

These points also apply to bioenergy, for which a major concern is the constraint on the bioenergy potential imposed by the low efficiency of photosynthesis. At some point, the limits of land will prevent expanding the use of bioenergy resources, bioenergy production costs will rise, and a shift will be required to more costly, less secure, or more environmentally troublesome resources. However, investments to promote the efficient conversion of biomass to gas, electricity, and other high-quality energy forms and the more efficient use of these energy forms (through, say, efficient

Table 7. Final Energy Use in the Residential Sector (Watts per capita)

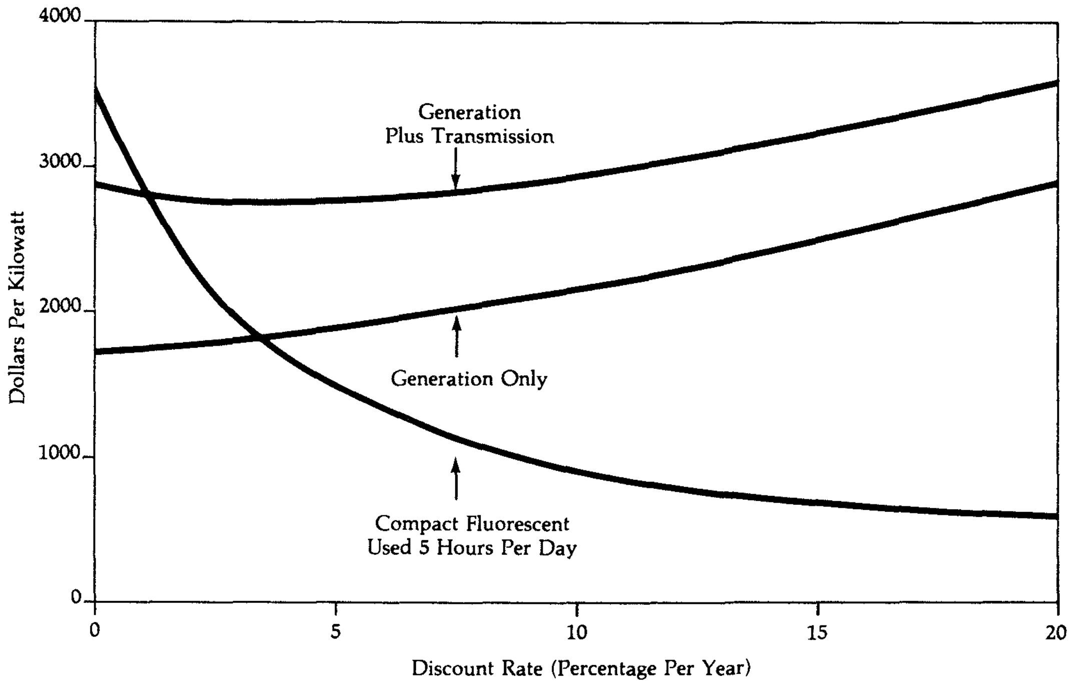
End-Use	Average Household at Present: United States, 1980[b]	Average Household at Present: Sweden 1972–1982[c]	All Electric, Four-Person Households with the Most Efficient Technology Available in 1982–1983[a]: United States	All Electric, Four-Person Households with the Most Efficient Technology Available in 1982–1983[a]: Sweden
Space Heat	890	900	60[d]	65[e]
Air Conditioning	46	-	65[f]	-
Hot Water	280	180	43[g]	110[h]
Refrigerator	79	17	25	8
Freezer	23	26	21	17
Stove	62	26	21	16
Lighting	41	30	18[i]	9[i]
Other	80	63	75	41
Total	1,501	1,242	328	266

a. With 100 percent saturation for the indicated appliances, plus dishwasher, clothes washer, and clothes dryer.
b. Total consists of 360 watts of electricity and 1,140 watts of fuel.
c. Total consists of 350 watts of electricity and 890 watts of fuel. Fifty percent of the electricity is for appliances and 50 percent is for heating purposes.
d. For an average-sized, detached, single-family house (150 square meters of floorspace); average U.S. climate (2,600 degree-days); a net heating requirement of 50 kilajoules per square meter per degree-day.[e] (Table 5): a heat pump with a seasonal average coefficient of performance (COP) of 2.6 (the highest efficiency for new air-to-air units).
e. For a Faluhus (Table 5) in a Stockholm climate (3,810 degree-days).This house uses a heat exchanger to transfer heat from the exhaust airstream to the incoming fresh air.
f. For the average cooling load in air-conditioned U.S. houses (27 gigajoules per year) and a COP of 3.3 (the COP on the cooling cycle for the most efficient heat pump available in 1982).
g. For 59 liters per capita per day of hot water (at 49° C) (or 910 kilowatt hours per year per capita) and the most efficient (COP of 2.2) heat pump water heater available, 1982.
h. For 1,000 kilowatt hours per year per capita hot water energy use via resistive heat. Ambient air-to-water heat pumps are not competitive at the low Swedish electricity prices.
i. Savings achieved by replacing incandescent bulbs with compact fluorescent bulbs.

gas stoves and electrical devices) would make it possible for bioenergy to play a much larger role in development.

Automobiles around the World. In 1982 automobiles used about 10 mbd,or one sixth of all oil used worldwide, equal to about three fourths of all oil produced in the Persian Gulf region that year. Automobiles are therefore

Figure 25. Life-Cycle Costs for Both Providing Peaking Hydroelectric Power and Saving Electricity Through Use of Compact Fluorescent Bulbs as Alternatives to Incandescents



The life-cycle cost shown is the discounted present value of the peaking electricity produced in a hydroelectric power system in Brazil or saved through the installation of compact fluorescent bulbs, in dollars per kilowatt measured at the household. All capital investments over the 50-year estimated lifetime of the hydroelectric power plant are included.

The cost of hydroelectric power supplies increases with the discount rate because of interest charges accumulated during construction. The cost for the more efficient light bulbs declines with the discount rate because replacement bulbs do not have to be purchased until they are needed.

Source: J. Goldemberg and R.H. Williams, "The Economics of Energy Conservation in Developing Countries," in *Energy Sources: Conservation and Renewables*, D. Hafmeister, H. Kelly, and B. Levi, eds., AIP Conference Proceedings, number 135 (New York: American Institute of Physics, 1985): 33-51.

prime candidates for energy-efficiency improvements.

Improved automotive fuel economy could have a significant impact on oil use in industrialized market-oriented countries, which account for four fifths of the world's cars and more than five sixths of the oil consumed by cars. *(See Table 8.)* About one fourth of all oil used in these countries fuels automobiles.

The automobile is rapidly becoming a major oil user in developing countries as well. The number of automobiles in developing countries

Table 8. Oil Use by Automobiles in 1982

Region	Number of Autos (millions)	Persons per Car	Oil Use[a] (million barrels per day)
Industrialized Countries			
United States	104.5	2.2	4.0
Canada	10.5	2.3	0.4
Other OECD	143.4	3.6	3.7
Eastern Europe, USSR	20.1	18.9	0.52
Subtotal	278.5	4.1	8.6
Developing Countries			
Africa	6.98	71.3	0.18
Latin America	23.35	15.7	0.61
Asia	9.92	246.7	0.26
(Asia except China, India)	8.94	81.2	0.23
Subtotal	40.25	82.3	1.04
World	318.8	14.0	9.6

a. In the United States the average auto had a fuel economy of 16.25 miles per gallon (14.5 liters per 100 kilometers) in 1982 and was driven 9,533 miles (15,340 kilometers). Here the same amount of annual driving is assumed for autos in other countries as well. The average fuel economy assumed for Canada is the same as for the United States. The average fuel economy for other regions is assumed to be 24 miles per gallon (9.8 liters per 100 kilometers).

grew at an average rate of 7.3 percent per year between 1975 and 1984, compared to 2.6 percent in the industrialized market-oriented countries. Moreover, the number of automobiles in developing countries is projected to increase 150 to 200 percent by the year 2000. *(See Table 9.)* If this increase occurs, the developing countries' share of the world's automobiles would increase from one eighth to about one fifth. If the average fuel economy of these new cars were the same as that outside the United States today—24 miles per gallon, or 9.8 liters per hundred kilometers—the increasing number of autos by itself would lead to a 1 percent annual increase in total oil use in the developing market-oriented countries between 1982 and the year 2000.

Aggressive efforts in both industrialized and developing countries to improve automotive fuel efficiency could forestall a rise in the world price of oil. Fortunately, technical opportunities for doing so abound.

In the late 1970s, most experts thought that only relatively modest improvements in fuel economy were feasible. For example, a major study in 1979 by the U.S. National Academy of Sciences (NAS) concluded that the likely technological limit on fuel economy achievable over

Table 9. The Automobile Population: Historical Data and Projections

	Developing Countries				Industrialized Countries			Fraction in Developing Countries
	Africa	Latin America	Asia	Subtotal	OECD	Eastern Europe	World	
	Historical Data (millions)							
1984	7.34	25.60	11.57	44.59	277.83	22.00	344.50	0.129
1983	7.45	24.78	10.11	42.34	270.82	21.20	334.55	0.127
1982	6.98	23.35	9.92	40.25	258.44	20.08	318.77	0.126
1981	6.64	21.17	9.18	36.99	257.59	18.96	313.54	0.118
1980	6.33	18.70	8.25	33.28	253.01	17.09	303.38	0.110
1979	5.85	17.21	8.01	31.07	247.55	15.31	293.93	0.106
1978	5.26	16.29	6.65	28.20	240.43	14.27	282.90	0.100
1977	4.92	15.50	6.86	27.28	232.71	12.58	272.57	0.100
1975	4.34	13.45	5.52	23.31	216.68	10.10	250.09	0.093
Growth Rates 1977–1984 (percent per year)	5.9	7.4	7.8	7.3	2.6	8.3	3.4	
	Projections to the Year 2000 (millions)							
MIT Study[a]				123.6	362.8	49.6	536	0.230
OECD Study	16	57	27	100	383	46	529	0.189
Averages				111.8	372.9	47.8	532.5	0.210
Growth Rates 1984–2000 (percent per year)								
MIT Study				6.6	1.7	5.2	2.8	
OECD Study				5.2	2.0	4.7	2.7	
Average				5.9	1.9	5.0	2.8	

Source: For MIT study: Massachusetts Institute of Technology International Automobile Program, *The Future of the Automobile* (Cambridge, Massachusetts: MIT Press, 1984). For OECD study: Organisation for Economic Co-operation and Development, *Long Term Outlook for the World Automobile Industry* (Paris, 1983).

a. For non-Organisation for Economic Co-operation and Development regions the projections in this study are actually for developing countries (excluding China) and for centrally planned economies (including China).

the next several decades was 37 mpg (6.4 lhk) because of its estimate that the total cost of owning and operating a car would rise sharply at higher fuel economy levels.[37]

Soon after the study was published, however, the more efficient Volkswagen Rabbit diesel and the Honda City Car were introduced. In the last couple years, the number of fuel-efficient models available has grown considerably. *(See Table 10.)* The most energy-efficient model available in the United States at this writing is the four-passenger, gasoline-fueled Sprint, which has an estimated on-the-road fuel economy of 57 mpg (4.1 lhk), some 50 percent higher than the NAS estimate of the "technological limit."[38]

Even these impressive new cars exploit only a fraction of the presently available technology for improving fuel economy. Most of the improvements to date are from reducing weight through use of lightweight materials, reducing rolling resistance through radial tires, reducing aerodynamic drag, and using pre-chamber diesel engine and lean-burn gasoline engines.

Options for making further gains with present technology include shifting to direct-injection diesel engines (the kind used in trucks) or spark-ignited, direct-injection diesel engines (which have multifuel capability), introducing the continuously variable transmission (CVT), introducing the feature of engine-off during idle and coast, using lightweight materials more extensively, and further reducing aerodynamic drag. Several prototype cars indicate what can be achieved using some of these technologies. *(See Table 10.)* The most recently introduced prototype, the Toyota AXV, a four- to five-passenger lightweight car with a direct-injection diesel engine, CVT, and a drag coefficient of 0.26, gets 98 mpg (2.4 lhk). *(See Figure 4.)*

But doesn't good fuel economy imply a sluggish vehicle that will make highway entry or passing difficult or dangerous? Not necessarily. The Volvo Light Component Project 2000 vehicle gets 65 mpg (3.6 lhk) but requires only 11 seconds to accelerate from 0 to 60 mph (96 km/hour), compared to 17 seconds for the popular automatic Chevrolet Cavalier, which has a fuel economy of only 28 mpg (8.4 lhk).[39] *(See Table 10.)*

Doesn't high fuel economy mean a tiny, cramped vehicle? Again, not necessarily. Most of the new highly efficient cars and prototypes listed carry four or five passengers comfortably.

Aren't fuel-efficient cars unsafe? Here too, good engineering design can improve the structural strength and safety of even very small cars. For example, the lightweight (707 kg) Volvo LCP 2000 can withstand 35-mph (56-km/hour) front and side impacts and 30-mph (48-km/hour) rear impacts—meeting stricter safety standards than do cars currently sold in the United States.[40] Moreover, advanced technology still under development will make it possible to build "heavy" fuel-efficient cars, such as the Cummins/NASA Lewis car design. *(See Table 10.)* This 80-mpg (2.9-lhk) car, equipped with a CVT and an advanced multifuel-capable, direct-injection adiabatic diesel engine and turbocompounding, would weigh 1,360 kg, approximately the average weight of new cars sold in the United States today.

One problem posed by diesel engines is that they emit on average about 100 times the weight of particulates produced by gasoline engines of comparable performance. However, Mercedes Benz and Volkswagen have developed emission-control devices that permit diesel cars to meet the strict 1986 California particulate limit of 0.2 grams per mile.[41] Moreover, the use of diesel fuel is not necessary to realize high fuel economy. Several highly efficient cars have gasoline engines, and spark-assisted diesel engines can have the fuel economy of diesels operating on gasoline or alternative fuels (e.g., ethanol or methanol). *(See Table 10.)*

Often the technologies added to cars to improve fuel economy cost more than the tech-

Table 10. Fuel Economy for Passenger Automobiles

Car	Fuel	Fuel Economy[a] liters per 100 kilometers	Fuel Economy[a] miles per gallon	Maximum Power (kilowatts)	Curb Weight (kilograms)	Passenger Capacity (persons)
Commercial						
1985 VW Golf, Jetta	diesel	5.0	47	39	1,029	5
1986 Honda CRX	gasoline	4.3	54	45	779	2
1985 Nissan Sentra	diesel	4.2	55	41	850	5
1985 Ford Escort	diesel	4.3	55	39	945	5
1986 Chevrolet Suzuki Sprint	gasoline	4.1	57	36	676	4
Prototype[b]						
VW Auto 2000[c]	diesel	3.6	66	39	780	4-5
Volvo LCP 2000[d]	multifuel	3.4	69	39/66	707	2-4
Renault EVE+[e]	diesel	3.4	70	37	855	4-5
Toyota Ltwght Compact[f]	diesel	2.4	98	42	650	4-5
Design						
Cummins/NASA Lewis Car[g]	multifuel	2.9	81	52	1,364	5-6

a. For diesel autos, fuel economy as measured in U.S. Environmental Protection Administration (EPA) test procedures; the combined fuel economy consists of a weighted average of 55 percent urban driving and 45 percent highway driving. For gasoline autos the fuel economy is a more recent EPA rating in which the EPA test values are modified to conform better to actual road performance: the fuel requirements (in liters per hundred kilometers) determined in the EPA test are divided by 0.9 (0.78) for urban (highway) driving. For diesels the EPA test is a good indicator of actual performance.

b. Fuel economies for the European and Japanese prototypes were converted to equivalent EPA test values, using conversion factors recommended by the International Energy Agency. Both the European Urban Cycle Test and the Japanese 10-Mode Test values for fuel requirements were converted to the EPA Urban Cycle Test values by dividing by 1.12. The European 90 kilometers per hour test value is equal to the U.S. highway test value. Fuel requirements measured in the Japanese 60 kilometers per hour test were multiplied by 1.15 to obtain the equivalent U.S. highway test value.

c. Three-cylinder, direct-injection (DI), turbocharged (TC) diesel engine; more interior space than the Rabbit; engine off during idle and coast; use of plastics and aluminum; drag coefficient of 0.26 (H.W. Grove and C. Voy, "Volkswagen Lightweight Component Project Vehicle Auto 2000," SAE Technical Paper No. 850104, presented at the SAE International Congress and Exposition, February 25-March 1, 1985).

Table 10. Continued

d. The 39-kilowatt car has a 3-cylinder, DI, TC, diesel engine. The 66-kilowatt car has a 3-cylinder, heat-insulated, TC, intercooled diesel engine with multifuel capability. Extensive use of aluminum, magnesium, and plastics; drag coefficient between 0.25 and 0.28 (R. Mellde, "Volvo LCP 2000 Light Component Project," SAE Technical Paper No. 850570, presented at the SAE International Congress and Exposition, February 25–March 1, 1985).
e. Supercharged, DI diesel engine; engine off during idle and coast; drag coefficient of 0.225 (Renault USA press release).
f. DI diesel engine, continuously variable transmission (CVT), wide use of plastics and aluminum, drag coefficient of 0.26 (Toyota press release, October 23, 1985).
g. Four-cylinder, DI, spark-assisted, multifuel capable, adiabatic diesel with turbocompounding; CVT; 1984 model Ford Tempo body (R.R. Sekar, R. Kamo, and J.C. Wood, "Advanced Adiabatic Diesel Engine for Passenger Cars," SAE Technical Paper No. 840434, presented at the SAE International Congress and Exposition, February 27–March 2, 1984).

nologies they replace. The costs of adding various fuel-saving technologies to a gasoline-powered 30-mpg (7.9-lhk) Volkswagen Rabbit costing $7,000 have been calculated by von Hippel and Levi.[42] *(See Figure 26.)* The estimated extra cost for adding all measures, which would raise the fuel economy to 90 mpg (2.6 lhk), is $1,725. This analysis indicates that the total cost of owning and operating a car would be roughly constant over the entire range from 30 mpg (7.9 lhk) to 90 mpg (2.6 lhk), a finding in sharp contrast to the 1979 NAS study, which suggested that the cost would rise sharply after a fuel economy of 37 mpg (6.4 lhk) was reached.[43]

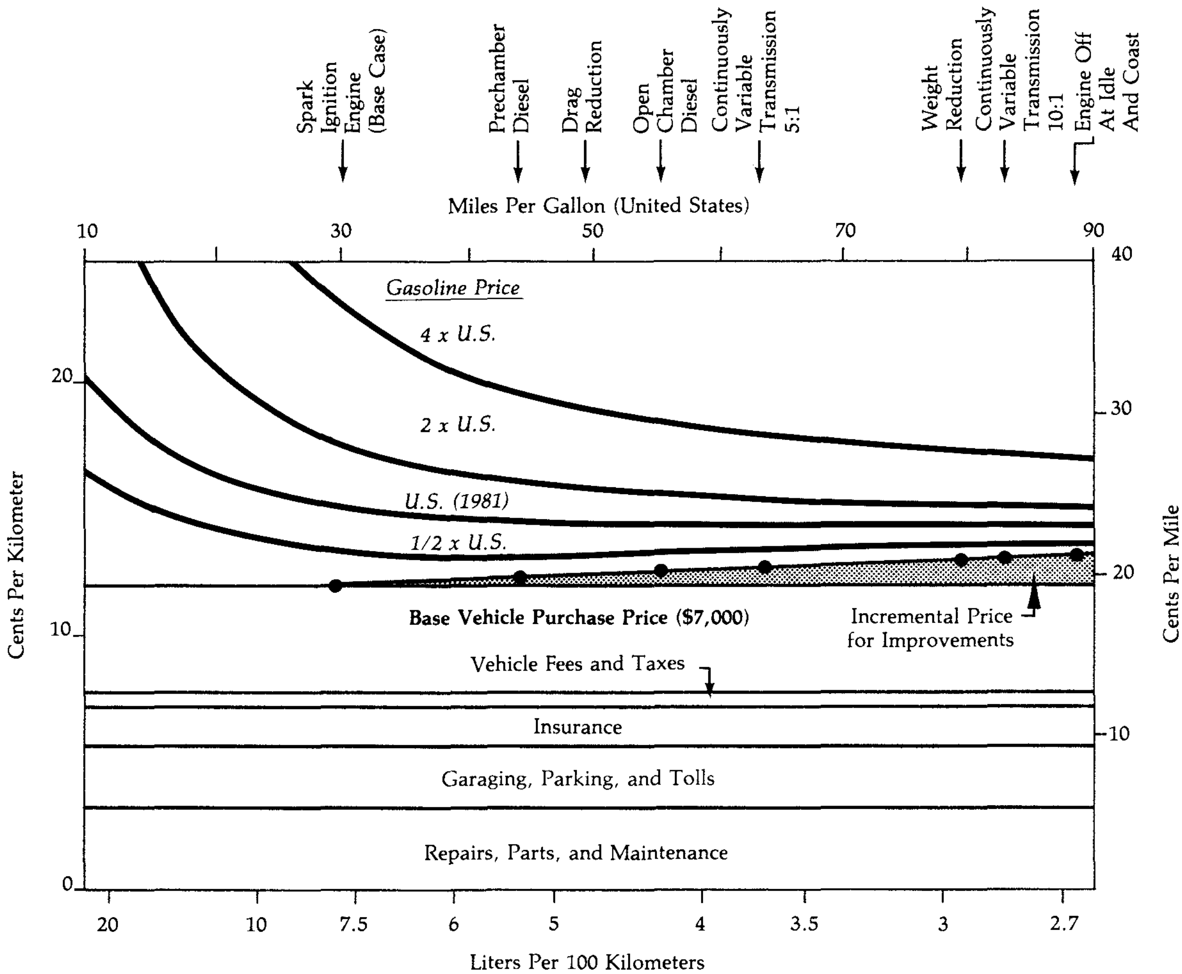
The von Hippel-Levi analysis may actually have overestimated the costs of fuel economy improvements. One reason is that most of the fuel-saving measures being explored by manufacturers offer consumer benefits other than just fuel savings, so that charging the extra costs exclusively to fuel economy is inappropriate. Consider the multiple benefits of the ongoing trend toward the use of more plastics in cars. Analysis by John Tumazos of Oppenheimer & Company indicates that greater use of plastics will reduce the cost of owning and operating a car in the United States by $150 to $250 per year because of longer product life from cheaper repairs, corrosion resistance, and lower insurance rates. The CVT would eliminate the noticeable jerkiness in shifting with automatic transmissions.[44]

The cost estimates of von Hippel and Levi may be too high for another reason too: the costs of improvements are not simply additive. Some extra costs may be offset by savings through related technological innovations. For example, the extensive use of plastics in auto bodies can cut fabrication and assembly costs. Such savings opportunies have led developers of the Volvo LCP 2000 to conclude that in mass production this car would cost the same as today's average subcompact.[45]

How much first costs will increase with fuel economy is still uncertain, though the arguments cited here suggest that the net increased first costs may be modest. High fuel economy can almost certainly be achieved without increasing life-cycle costs, as indicated by von Hippel and Levi.

If the goal for the average fuel economy of new cars in the mid-1990s were 60 mpg to 65 mpg (3.9 to 3.6 lhk), the average fuel economy for all cars on the road would be about 48 mpg (4.9 lhk) in the year 2000. If there were 112

Figure 26. The Cost of Driving Versus Automotive Fuel Economy



The indicated energy performance is based on computer simulations of an automobile having various fuel economy improvements added in the sequence shown at the top of the graph. The base car is a 1981 Volkswagen Rabbit (gasoline version).

The figure shows that the reduced operating costs associated with various fuel economy improvements are roughly offset by the increased capital costs of these improvements over a wide range of fuel economy.

Source: F. von Hippel and B.G. Levi, "Automotive Fuel Efficiency: The Opportunity and Weakness of Existing Market Incentives," *Resources and Conservation* (1983): 103-124.

million autos in developing countries in 2000 with this average fuel economy, the corresponding fuel use would be 1.4 mbd, only 40 percent higher than in 1982, despite a 180 percent increase in the number of cars. *(See Table 9.)* With 533 million autos worldwide in 2000 getting 48 mpg (4.9 lhk), global fuel use by cars would be about 6.7 mbd, 2.9 mbd *less* than in 1982. This reduction approximately equals the 2.8 mbd that FAO estimates is needed to double agricultural production in developing countries by the year 2000.[46]

It is doubtful, though, that market forces alone would quickly lead manufacturers to produce and consumers to buy these highly efficient cars. For one thing, consumers would probably not enjoy significant direct economic benefits by buying such a car. If the cost of owning and operating a car would remain essentially constant over the entire range from 30 mpg (7.9 lhk) to 90 mpg (2.6 lhk), then market forces certainly won't promote high fuel economy, because few consumers will pay more initially in return for savings in operating costs. Hence, market forces might push consumers to buy cars with fuel economies up to about 30 mpg (7.9 lhk), but not much beyond. Even if the von Hippel-Levi estimates of the cost of fuel economy improvements prove high, market forces may still provide only a weak incentive to seek high fuel economy, because for highly efficient cars, fuel costs represent a tiny fraction of the total cost of owning and operating a car. *(See Figure 26.)*

The value of fuel-efficient automobiles to society at large is much more clear-cut: they would reduce oil imports, help keep the world oil prices from rising, and promote global security.

In addition, if developing countries require their own car manufacturers to produce highly efficient cars, they would become more competitive in global car markets. The Hyundai Excel, a high-quality, low-cost subcompact car recently introduced in North American markets from Korea, is proving to be a strong competitor to U.S., Japanese, and Western European manufacturers. Brazil and Taiwan are also evolving into competitive, world-class car manufacturers. If these countries become not only automobile exporters but also exporters of highly efficient cars, they could promote the use of such cars in industrialized countries and enjoy the benefits of the lower world oil prices resulting from oil savings there.

Fuel savings from more efficient cars could be used to double agricultural production in developing countries by the year 2000.

Steelmaking and Technological Leapfrogging. About five sixths of all steel is produced in industrialized countries, where it accounts for a significant fraction of manufacturing energy use, for example, one sixth in Sweden and one seventh in the United States.

THE TECHNOLOGICAL POSSIBILITIES
Energy efficiency improvements have been pursued throughout the history of steelmaking, as is indicated by changing coking coal requirements for the blast furnace, the single largest energy user in the industry. In a blast furnace, hot air is blown through a stack of pieces of coke and chunks of iron ore and oxygen is transferred from the iron ore to the carbon, producing a combustible blast furnace and liquid pig iron, which is removed from the bottom. In 1804, about 5.5 tonnes of coking coal were required to produce a tonne of pig iron in England. The requirements in the United States had been reduced to 1.6 tonnes by 1913 and 0.9 tonnes by 1972.

Besides the energy needed for blast furnace operation, additional energy is required for other steps in conventional steelmaking: ore preparation and coke manufacture, operation of the steelmaking furnace, casting, rolling, and final fabrication. At each stage, there are opportunities to improve energy efficiency. The theoretical minimum amount of energy required to produce a tonne of steel is 7 gigajoules (GJ) from iron ore and 0.7 GJ from scrap.

At present, steelmaking in Sweden and the United States is based on a 50-50 mix of iron ore and scrap, so that the theoretical minimum is about 3.9 GJ per tonne of raw steel. The actual energy used to produce raw steel was 27 GJ per tonne in the United States in 1980 and 16 GJ per tonne in Sweden in 1983. *(See Table 11.)*

The Swedish steel industry has a better energy performance record, no doubt partly because it is relatively small and must be innovative to secure its place as a producer of specialty steels for export.

Potential energy-efficiency improvements in steel production can be illustrated by comparing four alternative technological structures for the Swedish steel industry. *(See Table 11.)* "Modern technology" refers to changes based on plans for the 1980s, which have largely been fulfilled. "Maximum heat recovery" represents the full exploitation of presently commercial technology for heat recovery, mostly by use of combustible gases in cogeneration

Table 11. Unit Energy Requirements for Raw Steel Production[a]

	Swedish Average, 1976	Swedish Average, 1983	Alternative New Technologies: Modern Technology[b]	Maximum Energy Recovery[c]	Elred[d]	Plasma-Smelt[e]	U.S. Average, 1980
			(gigajoules per tonne)				
Electricity[f]	2.9	3.2	1.8	1.8	1.3	4.2	2.0
Oil and Gas	7.6	2.8	4.3	2.2	1.3	1.3	7.5
Coal	11.9	10.3	9.0	9.0	9.4	3.3	17.5
Total	22.3	16.3	15.1	13.0	11.9	8.7	27.0

a. The mix of iron ore and scrap feedstocks is assumed to be 50/50, which is approximately the present average for both Sweden and the United States. The theoretical minimum energy required to produce a tonne of steel with this mix is 3.9 gigajoules.
b. This energy structure should result from changes planned in the late 1970s by the Swedish steel industry. Most of these improvements have already been achieved.
c. Same as "Modern Technology," except that the potential for energy recovery with presently commercial technology would be more fully exploited.
d. Same as "Modern Technology," except that the blast furnaces are replaced by a process called Elred, which is under development by Stora Kopparberg AB [S. Eketorp, et al., *The Future Steel Plant* (Stockholm: National Board for Technical Development, 1980)]
e. Same as "Modern Technology," except that the blast furnaces are replaced by a new process called Plasmasmelt, which is under development by SKF Steel AB. (S. Eketorp, et al., *The Future Steel Plant*).
f. Here electricity is evaluated at 3.6 megajoules per kilowatt hour (i.e., losses in generation, transmission, and distribution are not included).

(the combined production of heat and electricity). The Elred and Plasmasmelt processes are ironmaking processes now under development in Sweden.

However dramatic the energy-efficiency improvements offered by Elred and Plasmasmelt, interest in these technologies stems not so much from these features per se but, rather, from the prospect of overall cost reduction and environmental benefits. Specifically, with these processes:

- Powdered ores can be used directly, without having to agglomerate the ore into sinter or pellets. (Because lower- and lower-quality ores are being exploited, the required preliminary processing now leaves the ore concentrated in powdered form.)

- Ordinary steam coal can be used, greatly reducing the need to process more costly metallurgical coal into coke.

- Various individual operations can be integrated.

These new ironmaking processes near commercialization are by no means the ultimate in improving energy use and total productivity in the steel industry. Direct casting, direct steelmaking, and dry steelmaking all attempt to integrate separate operations to save capital, labor, and energy.[47] If the dry steelmaking technique is mastered, it will likely become the industry norm because with powder metallurgy the finished product is exceptionally uniform in quality.

APPLICATIONS TO DEVELOPING COUNTRIES Steel demand can be expected to grow rapidly in developing countries as they industrialize. In expanding their steel industries, should developing countries adopt the mature technologies of the industrialized countries? Or should they instead develop more advanced technologies? Conventional wisdom holds that developing countries cannot afford the risks associated with new process development and should instead stick with the tried and true.

Nevertheless, the reasons for pursuing advanced technologies are powerful. In the steel industry energy-saving innovations are needed to offset new higher energy prices. Yet, the industrialized countries are not providing advanced technologies because their own declining steel demand creates a poor economic climate for innovation. *(See Figures 16 and 17.)*

Additionally, the comparative advantages of using human, financial, and natural resources are often quite different in countries of the South than in the North. Many of the industrial technologies commercialized in the North are capital-intensive and labor-saving—characteristics not well-suited to the South, where labor is cheap and abundant and capital costly and scarce. Many developing countries are also blessed with largely undeveloped and relatively low-cost hydroelectric resources, whereas most industrialized countries must rely on more costly thermal sources for increased electrical capacity. Similarly, biomass is a promising source of chemical fuels for many developing countries, requiring decentralized development strategies quite unlike the centralized strategies that have been pursued by the countries rich in fossil fuels.

For such reasons, developing countries should examine the range of advanced technological possibilities and pursue those compatible with their development goals and resources.[48] For some industrializing countries with little coal but rich water resources, the electricity-intensive Plasmasmelt process might be an attractive technology. For countries with neither of these resources but with significant natural gas, direct-reduction ironmaking (in which iron ore is converted into sponge iron at temperatures below the melting point, using a wide variety of reductants, including natural gas) may be more appropriate. Or entirely new technologies tailored to conditions in the South may be preferable.

Brazil's experience with charcoal-based steelmaking demonstrates the feasibility of "technological leapfrogging," the introduction of a competitive advanced industrial technology in the South before it is introduced in the North. In industrialized countries, coke began to replace charcoal as a reducing agent for ironmaking in the mid-18th Century. The shift to coke led to much larger blast furnaces than were possible with charcoal because coke can better resist crushing under the load of the furnace charge.

Although most of the world's steel industry is now based on coke, 37 percent of Brazilian steel production, 4.9 million tonnes, was based on charcoal in 1983. This anomaly reflects the scarcity of high-quality coking coal in Brazil. Although charcoal-based steel production is widely viewed as anachronistic, it produces better quality steel because charcoal has fewer impurities than coke. Brazilian charcoal-based steel competes well in world markets because the industry is far more advanced than the charcoal-based industry abandoned long ago by industrialized countries.

Brazil's demonstration that charcoal-based steel produced by blast furnaces processing hundreds of tonnes per day can compete with coke-based furnaces processing thousands of tonnes per day is an important lesson for developing countries generally. The technology is labor-intensive, it is well-matched to the resource bases of countries rich in biomass but poor in fossil fuels, and the scale of its installations often permits increments in productive capacity more appropriate to the size of local markets than giant coke-based facilities.

The major cost item in charcoal-based ironmaking is charcoal, which accounts for 65 percent of total pig iron production costs in Brazil. Charcoal for steelmaking there is produced mainly with wood from plantations of pine and eucalyptus, for which the planted area exceeded 5 million hectares in 1983.

Technical developments relating to charcoal-based steel production are advancing rapidly. *(See Table 12.)* Plantation yield has roughly doubled over the last decade, and a further 50-percent increase is expected. Over the last decade, charcoal yields from wood have also improved about 20 percent, and another 10-percent increase is expected shortly. At the same time, charcoal requirements for ironmaking have been lowered. Thanks to these improvements, the land area required for a given level of steel production is soon expected to be just one fifth that required in the 1970s.

Clearly, technological leapfrogging can be accomplished in developing countries. But new technologies must be compatible with local resources and support broad development goals as well as reduce direct costs.

Case Studies: Sweden and the United States

To show the potential impact on future energy demand in industrialized countries of (1) structural economic shifts toward less energy-intensive activities and (2) the possibilities for more efficient energy use, we have constructed detailed demand scenarios for Sweden and the United States in the year 2020, details of which are presented elsewhere.[49]

These scenarios were constructed "from the bottom up." The starting point was the development of a detailed picture of present energy consumption disaggregated by end-uses for each energy-consuming sector: residences, commercial buildings, transportation, and industry. Then, future activity levels (such as passenger-kilometers of air travel or liters of hot water per household) were estimated using the most likely population projections and alternative economic growth assumptions, based on historical trends modified according to identifiable structural shifts. Finally, the projected activity levels were matched to energy intensities (e.g., kilojoules of kerosene per passenger-kilometer of air travel or kilojoules of natural gas per liter of hot water) characteristic

Table 12. Parameters Relating to the Annual Production of 1 Million Tonnes of Steel Based on Charcoal in Brazil

	70s Decade	80s Decade	Near Future
Wood Yield on Plantations (tonnes per hectare per year)[a]	12.5	25	37.5
Wood-to-Charcoal Conversion Rate (cubic meters per tonne)	0.67	0.80	0.87
Specific Charcoal Consumption (cubic meters per tonne of pig iron)	3.5	3.2	2.9
Required Area for Plantations (thousand hectares)	336	128	71
Investment Required to Establish Forest (million U.S. dollars)	201.6	76.8	42.6

a. Air dry tonnes (25 percent moisture).

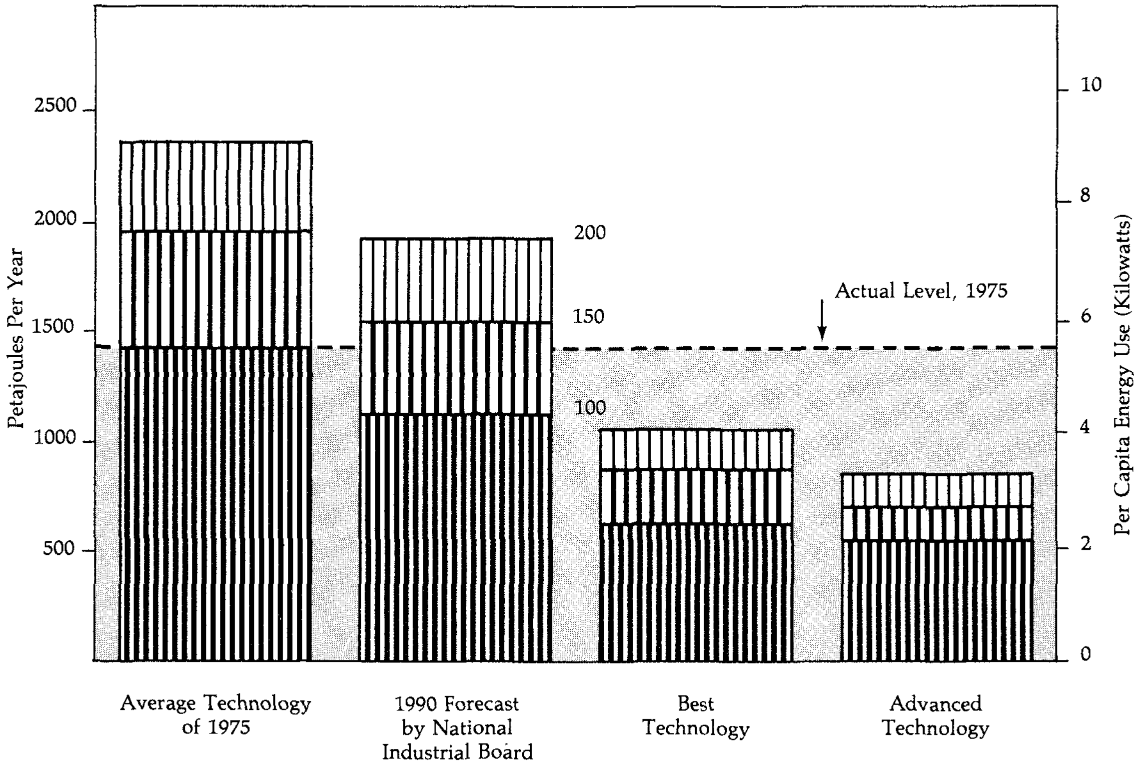
of selected energy-efficient technologies considered economical on a life-cycle cost basis. (The new technologies were assumed to be introduced at the rates of capital stock turnover and growth.) Finally, future aggregate energy demand estimates were obtained by multiplying the activity levels by their corresponding energy intensities and summing up activities in all sectors.

Sweden. Although per capita gross domestic product in Sweden is comparable to that in the United States, final energy use per capita is only about three fifths as large—averaging 5.3 kW per capita in both 1975 and 1980. Although Sweden is generally seen as a model energy-conserving society, there are major opportunities for energy savings.

Our analysis shows that with use of energy-efficient end-use technology now commercially available, Sweden's per capita final energy use could be reduced to about 3.5 kW with a 50-percent increase in the per capita consumption of goods and services and to 4.2 kW with a 100-percent increase in goods and services. In looking to the year 2020, it may be more appropriate to consider instead advanced end-use technologies still under development that are estimated to be cost-effective. In this case, per capita final energy use could be reduced to about 2.7 kW or 3.3 kW, depending on whether the per capita consumption of goods and services increases 50 or 100 percent. *(See Figure 27 and Tables 13, 14, and 15.)*

The United States. U.S. per capita final energy use averaged 9 kW in 1980, two and one half times that of Western Europe and Japan and ten times that of developing countries. With 5 percent of the world's population, the United States accounts for one fourth of global energy use. Thus, U.S. energy consumption has a major impact on such global energy-related problems as cartel control of the world oil market and the security difficulties that go with it, the

Figure 27. Final Energy Demand in Sweden for Four Levels of Energy Intensity at 100, 150, and 200 Percent of the 1975 Level of Consumption of Goods and Services



carbon dioxide build-up in the atmosphere, and the great disparity in commercial energy distribution between rich and poor countries.

Per capita final energy consumption could be reduced to 4.3 kW with a 50-percent increase in per capita GNP or to 4.6 kW with a 100-percent increase in per capita GNP if cost-effective, energy-efficient technologies are used. *(See Tables 16, 17, 18, and 19.)*

Because U.S. energy use is currently so high, the projected reduction in aggregate U.S. energy use between 1980 and 2020 is very significant globally—about 0.71 to 0.87 TW-years per year, which is equal to 25 to 30 percent of all energy used in developing countries in 1980.

Conclusion

Given these results for Sweden and the United States and the broad applicability of the technologies considered in these analyses, it is reasonable to expect that a 50-percent reduction in per capita final energy use, from 4.9 to 2.5 kW, is achievable on average for all industrialized countries between 1980 and 2020, at the same time that standards of living improve significantly. This projection forms the basis for our scenario for industrialized countries. *(See Figure 9.)* Our analyses for Sweden and the

Table 13. Final Energy Use Scenarios for Sweden[a]

	1975			Consumption of Goods and Services Up 50 Percent: Present Best Technology			Consumption of Goods and Services Up 50 Percent: Advanced Technology		
	Fuel	Electricity	Total	Fuel	Electricity	Total	Fuel	Electricity	Total
	(Petajoules per year[b])								
Residential[c]	295	61	356	61	65	126	36	54	90
Commercial[d]	104	36	140	11	39	50	3	37	40
Transportation									
Domestic	223	11	234	183	11	194	137	7	144
International Bunkers	47	-	47	32	-	32	25	—	25
Industry									
Manufacturing	410	137	547	293	153	446	230	141	371
Agriculture, Forestry, and Construction	65	14	79	40	21	61	37	13	50
Total	1141	259	1400	622	289	911	467	253	720

a. The population is assumed to be 8.3 million in all cases. The per capita gross domestic product in 1975 was $8,320.
b. One petajoule equals 10^{15} joules. One petajoule per year is equivalent to 448 barrels of oil per day.
c. Heated residential floor space is assumed to increase from 36 square meters per capita in 1975 to 55 (73) square meters per capita with a 50 percent (100 percent) increase in per capita consumption of goods and services.
d. Commercial buildings' floor space is assumed to increase from 12.7 to 16.4 (20.2) square meters per capita for a 50 percent (100 percent) increase in per capita consumption of goods and services.

United States suggest that this scenario would be technically and economically feasible. And although it is not a prediction, it is consistent with plausible values of future energy prices, income elasticities, and price elasticities associated with a 50- to 100-percent increase in per capita GDP between 1980 and 2020. *(See Appendix.)*

As noted, many efficiency improvements will be made automatically as the capital stock grows and turns over. Accordingly, the recent downward trend in per capita energy use in market-oriented industrialized countries is likely to continue. Nevertheless, a 50-percent reduction in per capita energy use will probably not occur unless governments clear away some of the obstacles—market imperfections and other institutional impediments—to exploiting energy efficiency opportunities.

Probably the greatest uncertainty regarding

Table 13. Continued

	Consumption of Goods and Services Up 100 Percent					
	Present Best Technology			Advanced Technology		
	Fuel	Electricity	Total	Fuel	Electricity	Total
			(Petajoules per year[b])			
Residential[c]	78	73	151	50	58	108
Commercial[d]	11	41	54	5	38	43
Transportation						
Domestic	210	13	223	160	9	169
International Bunkers	40	-	40	29	-	29
Industry						
Manufacturing	353	191	544	275	175	450
Agriculture, Forestry, and Construction	54	29	83	49	19	68
Total	751	347	1098	569	299	868

our scenario is how far the centrally planned industrialized countries of Eastern Europe and the Soviet Union will pursue energy efficiency. To date at least, they have adopted few energy-efficiency improvements. However, pressures to use energy efficiently are mounting. Oil production in the Soviet Union has peaked and will probably decline slowly in the future. The easy-to-exploit coal resources in the western part of the Soviet Union are being exhausted, so that coal production is shifting to remote Siberian sources. And even before the Chernobyl accident, nuclear power was proving to be more costly than expected and its expansion was well behind schedule. Moreover, because average per capita energy use in these countries is about the same as in market-oriented industrialized countries, and the level of amenities made possible by energy are probably higher in the West than in the East, it may be true that what can be achieved in a few countries such as Sweden and the United States is feasible in any industrialized country.

Energy Use in Developing Countries—A Thought Experiment

The energy demand situation is completely different for the three quarters of the world's population who live in developing countries and account for one third of world energy use. At present, per capita final energy use in developing countries averages about 0.9 kW, of which about 0.4 kW is non-commercial energy, most of it used by the two thirds of the population who live in rural areas.

Current patterns of energy end use in various developing countries are not nearly as well-understood as those in industrialized countries. The available data are not nearly as

Table 14. Final Per Capita Energy Use Scenarios for Sweden[a]

	1975	With Consumption of Goods and Services Up 50 percent: Present Best Technology	With Consumption of Goods and Services Up 50 percent: Advanced Technology	With Consumption of Goods and Services Up 100 percent: Present Best Technology	With Consumption of Goods and Services Up 100 percent: Advanced Technology
		(kW per Capita)			
Residential[b]	1.36	0.48	0.34	0.58	0.41
Commercial[c]	0.53	0.19	0.15	0.21	0.16
Transportation					
Domestic	0.89	0.74	0.55	0.85	0.65
International Bunkers	0.18	0.12	0.10	0.15	0.11
Industry					
Manufacturing	2.09	1.70	1.42	2.08	1.72
Agriculture, Forestry, and Construction	0.30	0.23	0.19	0.31	0.26
Total	5.34	3.48	2.75	4.19	3.31

a. The population is assumed to be 8.3 million in all cases. The per capita gross domestic product in 1975 was $8,320.
b. Heated residential floor space is assumed to increase from 36 square meters per capita in 1975 to 55 (73) square meters per capita with a 50 percent (100 percent) increase in per capita consumption of goods and services.
c. Commercial buildings' floor space is assumed to increase from 12.7 to 16.4 (20.2) square meters per capita for a 50 percent (100 percent) increase in per capita consumption of goods and services.

comprehensive, and it is inherently more difficult to project long-range energy demand for rapidly industrializing countries than for mature industrialized countries where most energy-intensive activities are growing only slowly or not at all.

In the face of such problems, a different approach for estimating long-term energy requirements in developing countries makes sense. Imagine for argument's sake a developing country having a standard of living roughly equal to that in Western Europe, Japan, Australia, and New Zealand in the late 1970s.[49] *(See Table 20.)* In other words, the average family lives in a reasonably well-constructed house with running water, plumbing for sewage, an easy-to-use cooking fuel (such as gas), electric lights, and all basic appliances—refrigerator-freezer, a water heater, a clothes washer, and a television set. There is one automobile for every 1.2 households on aver-

Table 15. Disaggregated Energy Use Scenarios for Swedish Transportation and Manufacturing

		Consumption of Goods and Services Up 50 Percent		Consumption of Goods and Services Up 100 Percent	
	1979[a]	Present Best Technology	Advanced Technology	Present Best Technology	Advanced Technology
			(Petajoules per year)		
Domestic Transportation					
Automobiles[b]	148	86	54	101	65
Trucks[c]	50	43	29	47	32
Rail Freight[d]	4	4	4	7	7
Other	50	61	58	65	65
Total	252	194	145	223	169
	1975				
Manufacturing					
Pulp and Paper[e]	212	148	122	148	122
Iron and Steel[f]	119	76	61	86	72
Fabrication and Finishing	54	61	54	90	76
Cement	40	36	32	47	40
Chemical	32	36	36	50	47
Other	90	90	65	122	94
Total	547	446	371	544	450

a. Transportation data disaggregated by end-use are not available for 1975.
b. The number of person-kilometers of car travel is assumed to increase from the 1979 level of 41 billion by 25 percent (50 percent), for the case of a 50 percent (100 percent) increase in the per capita consumption of goods and services.
c. The volume of truck freight is assumed to increase from the 1979 level of 14 billion tonne-kilometers by 12.5 percent (25 percent), for the case of a 50 percent (100 percent) increase in the per capita consumption of goods and services.
d. The volume of rail freight is assumed to increase by 60 percent (120 percent), for the case of a 50 percent (100 percent) increase in the per capita consumption of goods and services.
e. Production in the paper and pulp sector was limited to a 50 percent increase over the 1975 level in both cases because of limited raw material supply.
f. Because of the considerable competition faced by the export-oriented Swedish steel industry, the output of the steel industry is assumed to be only 23 percent (44 percent) higher than in 1975, if per capita consumption of goods and services increases 50 percent (100 percent).

Table 16. Alternative Scenarios for Total and Per Capita Final Energy Use in the United States

Actual Energy Use in 1980

	Fuel	Total Electricity	Total	Per Capita
	(Exajoules per year[a])			(kilowatts)
Residential[b]	8.0	2.6	10.7	1.5
Commercial[b]	4.3	2.0	6.3	0.9
Transportation[c]	20.8	-	20.8	2.9
Industry[d]	23.7	3.0	26.7	3.7
Total	56.8	7.6	64.4	9.0

Projected Energy Use in 2020

	Gross National Product per Capita Up 50 Percent				Gross National Product per Capita Up 100 Percent			
	Fuel	Total Electricity	Total	Per Capita	Fuel	Total Electricity	Total	Per Capita
	(Exajoules per year[a])			(kilowatts)	(Exajoules per year[a])			(kilowatts)
Residential[b]	3.3	2.0	5.3	0.6	3.3	2.0	5.3	0.6
Commercial[b]	1.4	1.8	3.2	0.3	1.4	1.8	3.2	0.3
Transportation[c]	12.4	0.2	12.6	1.3	14.3	0.2	14.5	1.5
Industry[d]	14.1	4.7	18.8	2.0	15.1	5.1	20.2	2.2
Total	31.2	8.7	39.9	4.3	34.1	9.1	43.2	4.6

a. One exajoule equals 10^{18} joules. One exajoule per year is equivalent to 448,000 barrels of oil per day.
b. See Table 17.
c. See Table 18.
d. See Table 19.

age, and air travel per person averages 350 kilometers per year. Moreover, an industrial and service infrastructure is in place to sustain this standard of living.

Now further suppose that the energy-using technologies furnishing energy services have efficiencies comparable to those of the most energy-efficient technologies commercially available or of advanced technologies that could be available in the next decade. *(See Table 21.)* Most of the technologies indicated here—the water heaters, light bulbs, cement plants, paper mills, nitrogen fertilizer plants, etc.—are

Table 17. Final Energy Use Scenario for the U.S. Residential and Commercial Sectors[a]

Residential Sector[b]

End Use	**Millions of Units in Use**				**Annual Energy Use in Exajoules**			
	1980		**2020**		**1980**		**2020**	
	Electricity	**Fuel**	**Electricity**	**Fuel**	**Electricity**	**Fuel**	**Electricity**	**Fuel**
Space Heat	14.3	66.7	43.4	75.8	0.29	6.02	0.19	1.93
Air Conditioning								
Central	22.2	-	62.4	-	0.24	-	0.37	-
Room (#HH w)	24.8	-	19.0	-	0.09	-	0.04	-
Hot Water	26.1	55.3	43.4	75.8	0.33	1.64	0.14	0.67
Refrig/Freezer	93.0	-	119.2	-	0.56	-	0.25	-
Freezer	33.7	-	119.2	-	0.16	-	0.24	-
Range	44.4	37.1	43.4	75.8	0.12	0.28	0.12	0.40
Dryer	38.3	11.8	43.4	75.8	0.16	0.06	0.14	0.33
Lights	81.6	-	119.2	-	0.29	-	0.13	-
Miscellaneous					0.34	-	0.34	-
Total					2.59	8.00	1.96	3.33

Commercial Sector[c]

	Commercial Floor Area		**Annual Energy Use in Exajoules**			
			Electricity	**Fuel**	**Electricity**	**Fuel**
	1980	**2020**	**1980**		**2020**	
	(billion square meters)					
Total	4.23	6.37	2.03	4.34	1.80	1.40

a. In accord with U.S. conventions, final energy use is defined as primary energy use less losses in the generation, transmission, and distribution of electricity. Losses associated with petroleum refining and transport are counted as final energy use by the industrial and transport sectors, respectively.

b. Because of a 30 percent increase in the population and a decline in the average household size from 2.8 persons in 1980 to 2.4 persons in 2020 the number of households increases from 82 to 119 million from 1980 to 2020. It is assumed that the amount of heated floor space per capita increases from 50 square meters in 1980 to 58 square meters in 2020. One hundred percent saturation is assumed for the ownership of all major appliances except air-conditioning. The assumption that the ownership level is thus independent of gross national product simplifies the analysis with little loss of generality, because of the already high level of use of major energy-using appliances. Household amenities that are income-sensitive are of little consequence in terms of energy use. For air conditioning the saturation is assumed to be two thirds, because in most parts of the country where it is not yet common, air conditioning is not needed.

c. The projection for commercial floor space is based on a regression against service sector employment for the period 1970–1979, which indicates that for a 65 percent increase in service sector employment from 1980 to 2020, there would be a 50 percent increase in commercial floor space.

Table 18. Alternative Final Energy Use Scenarios for the U.S. Transportation Sector

Transport Mode	1980 Fuel	1980 Electricity	2020 Fuel	2020 Electricity
	(Exajoules per year)			
Automobiles and Light Trucks	12.3	-	3.5[a]	-
Commercial Air Passenger Transport	1.6[b]	-	3.5[c]	-
Intercity Truck Freight	1.6[d]	-	1.9[e]	-
Rail Freight	0.6[f]	-	0.7[g]	0.2[g]
Other	4.7	-	4.7	-
Total	20.8	-	14.3	0.2

a. It is assumed that the number of light vehicles per person aged 16 and over is 0.80 (compared to 0.78 in 1980), that the average light vehicle is driven 17,000 kilometers (10,600 miles) per year, the same amount as in 1980, and that the average fuel economy of light vehicles is increased to 3.1 liters per 100 kilometers (75 miles per gallon) by 2020.
b. For 420.6 billion person-kilometers at 3.82 megajoules per person-kilometer.
c. It is assumed that revenues grow 1.64 times as fast as GNP, continuing the trend of the 1970s; revenue per people-kilometer remains constant at the 1980 level; and the average energy intensity of air travel is reduced in half between 1980 and 2020.
d. For 825 billion tonne-kilometer of intercity truck freight at 2.0 megajoules per tonne-kilometer.
e. It is assumed that the volume of truck plus rail freight grows 0.86 times as fast as gross national product, continuing the trend of the 1970s; the truck-rail mix of freight doesn't change; and the energy intensity of truck freight is reduced in half between 1980 and 2020.
f. For 1,345 billion tonne-kilometer at 470 kilajoules per tonne-kilometer.
g. It is assumed that, by 2020, one half of rail freight is electrified and that the final energy intensity of electric rail freight is one third of that for diesel rail freight.

Probably the greatest uncertainty is how far the centrally planned industrialized countries of Eastern Europe and the Soviet Union will pursue energy efficiency.

on the market today. None requires technological breakthroughs, and all will probably be cost-effective at present energy prices.

To complete the "thought experiment," multiply each activity level in Table 20 by the corresponding specific energy requirement in Table 21, and then sum them up. *(See Table 22 and Figure 28.)* The results are remarkable. In this hypothetical developing country, people enjoy a Western European standard of living with a total final energy demand of about 1 kW per capita, only slightly more than at present.

How is this possible? Great improvements in living standards can be achieved without increasing energy use much, in part by adopting the more energy-efficient technologies now

Table 19. Alternative Final Energy Use Scenarios for the U.S. Industrial Sector

	1972	1980	2020 Gross National Product per Capita Up 50 Percent	2020 Gross National Product per Capita Up 100 Percent
Industrial Output (billion 1972 dollars)[a]	406.1	464.7	837	1074
Annual Fuel Use (exajoules)[b]	25.2	23.7	14.1[c]	15.1[c]
Annual Electricity Use (exajoules)	2.3	3.0	4.7[c,d]	5.1[c,d]
Fuel Intensity (megajoules per 1972 dollar)	62.1	51.0	16.8	14.1
Electricity Intensity (megajoules per 1972 dollar)	5.7	6.4	5.6	4.7
Final Energy Intensity (megajoules per 1972 dollar)	67.8	57.5	22.5	18.8

a. Industrial output is gross product originating in industry (manufacturing, construction, mining, and agriculture, forestry, and fisheries). Following the trend established in the 1970s, industrial output is assumed to grow 0.83 times as fast as gross national product.
b. Includes wood.
c. Final energy use for the year 2020 is determined by assuming that (1) the outputs of the basic materials processing (BMP) and mining, agriculture, and construction (MAC) subsectors of industry grow only as fast as the population between 1980 and 2020, because of demand saturation, and (2) the average energy intensity of each industrial subsector [BMP, MAC, and other manufacturing (OMFG)] is reduced in half between 1980 and 2020, via energy efficiency improvements. Assumption (1) implies that from 1980 to 2020 the BMP and MAC subsectors grow 30 percent and the OMFG subsector grows 130 percent and 230 percent, associated with a 50 percent and 100 percent increase in per capita gross national product, respectively.
d. The electrical fraction of final energy use in industry in 2020 is assumed to be 0.25 (up from 0.11 in 1980). This increase is based on the assumed persistence of the relationship established in the 1970s between the electrical fraction of final industrial energy use and time.

becoming available in industrialized countries. In addition, enormous increases in energy efficiency arise simply by shifting from traditional inefficiently used non-commercial fuels (such as cattle dung, crop residue, and wood) to modern energy carriers (such as electricity, gas, and processed solid fuels). The importance of shifting to modern carriers is evident from the fact that in Western Europe (where non-commercial fuel use is very low) per capita final energy use (for all purposes except space heating) in 1975 averaged 2.3 kW, only two and a half times what it was in developing countries, even though the per capita gross domestic product in Western Europe was ten times as large as in developing countries.

In the 1-kW scenario, the residential sector contributes much less to total energy use than it does now. The residential sector today ac-

Table 20. Activity Levels for a Hypothetical Developing Country in a Warm Climate, with Amenities (Except for Space Heating) Comparable to Those in the WE/JANZ[a] Region in the 1970s

Activity	**Activity Level**
Residential[b]	4 persons per household
Cooking	Typical cooking level with liquid petroleum gas stoves[c]
Hot Water	50 liters of hot water per capita per day[d]
Refrigeration	One 315-liter refrigerator-freezer per household
Lights	New Jersey (USA) level of lighting
TV	1 color TV per household, 4 hours per day
Clothes Washer	1/HH, 1 cycle/day
Commercial	5.4 square meters of floor space per capita (WE/JANZ average, 1975)
Transportation	
Automobiles	0.19 autos per capita, 15,000 kilometers per auto per year (WE/JANZ average, 1975)
Intercity Bus	1850 person-kilometer per capita per year (WE/JANZ average, 1975)
Passenger Train	3175 person-kilometer per capita per year (WE/JANZ average, 1975)[e]
Urban Mass Transit	520 person-kilometer per capita per year (WE/JANZ average, 1975)[f]
Air Travel	345 person-kilometer per capita per year (WE/JANZ average, 1975)
Truck Freight	1495 tonne-kilometer per capita per year (WE/JANZ average, 1975)
Rail Freight	814 tonne-kilometer per capita per year (WE/JANZ average, 1975)
Water Freight	one half OECD Europe average, 1978[g]
Manufacturing	
Raw Steel	320 kilogram per capita per year (OECD Europe average,1978)
Cement	479 kilogram per capita per year (OECD Europe average, 1980)
Primary Aluminum	9.7 kilogram per capita per year (OECD Europe average, 1980)
Paper and Paperboard	106 kilogram per capita per year (OECD Europe average, 1979)
Nitrogenous Fertilizer	26 kilogram of nitrogen per capita per year (OECD Europe average, 1979–1980)
Agriculture	WE/JANZ average, 1975
Mining, Construction	WE/JANZ average, 1975

a. WE/JANZ stands for Western Europe, Japan, Australia, New Zealand, and South Africa.
b. Activity levels for residences are estimates, owing to poor data for the WE/JANZ region.
c. Equivalent in terms of heat delivered to the cooking vessels, to using one 13 kilogram canister of liquid petroleum gas per month for a family of 5.
d. For water heated from 20 to 50°C.
e. In 1975 the diesel-electric mix was in the ratio 70/30.
f. In 1975 the diesel-electric mix was in the ratio 60/40.
g. The tonne-km per capita of water freight in 1978 in OECD Europe is assumed to be reduced in half because of reduced oil use (58% of Western European import tonnage and 29% of that of exports were oil in 1977) and emphasis on self reliance.

Table 21. Assumed End-Use Technologies and Their Energy Performance Levels for the Hypothetical Developing Country Described in the Text

Activity	Technology, Performance
Residential	
Cooking	70 percent efficient gas stove[a]
Hot Water	heat pump water heater, coefficient of performance of 2.5[b]
Refrigeration	Electrolux refrigerator-freezer, 475 kilowatt-hours per year
Lights	Compact fluorescent bulbs
TV	75-watt unit
Clothes Washer	0.2 kilowatt-hours per cycle[c]
Commercial	performance of Harnosand Building (all uses except space heating)[d]
Transportation	
Automobiles	Cummins/NASA Lewis Car at 3.0 liters per 100 kilometers[e]
Intercity Bus	three-fourths energy intensity in 1975[f]
Passenger Train	three-fourths energy intensity in 1975[g]
Urban Mass Transit	three-fourths energy intensity in 1975[h]
Air Travel	one-half U.S. energy intensity in 1980[i]
Truck Freight	0.67 megajoules per tonne-kilometer[j]
Rail Freight	electric rail at 0.18 megajoules per tonne-kilometer[k]
Water Freight	60 percent of OECD energy intensity[l]
Manufacturing	
Raw Steel	average, Plasmasmelt and Elred Processes
Cement	Swedish average, 1983[m]
Primary Aluminum	Alcoa process[n]
Paper and Paperboard	average of 1977 Swedish designs[o]
Nitrogenous Fertilizer	ammonia derived from methane[p]
Agriculture	three-fourths WE/JANZ energy intensity[q]
Mining, Construction	three-fourths WE/JANZ energy intensity[q]

a. Compared to an assumed 50 percent efficiency for existing gas stoves; 70 percent efficient stoves having low NO_X emissions, have been developed for the Gas Research Institute in the United States (K.C. Shukla and J.R. Hurley, "Development of an Efficient, Low NO_X Domestic Gas Range Cook Top," GRI/81/0201, Gas Research Institute, Chicago, 1983).
b. The assumed heat pump performance is comparable to that of the most efficient heat pump water heaters available in the United States in 1982.
c. Typical value for U.S. washing machines.
d. The Harnosand Building was the most energy-efficient commercial building in Sweden in 1981, at the time it was built. It used 0.13 gigajoules of electricity per square meter of floor area for all purposes other than space heating.
e. See Table 10.
f. A 25 percent reduction in energy intensity is assumed relative to the 1975 average of 0.60 megajoules per person-kilometer for intercity buses, owing to the introduction of adiabatic diesels with turbocompounding.

Table 21. Continued

g. A 25 percent reduction in energy intensity is assumed relative to the 1975 average of 0.60 (0.20) megajoules per person-kilometer for diesel (electric) passenger trains, owing to the introduction of adiabatic diesels with turbocompounding (electric motor control technology).
h. A 25 percent reduction in energy intensity is assumed relative to the 1975 average of 1.13 (0.41) megajoules per person-kilometer for diesel buses (electric mass transit), owing to the introduction of adiabatic diesels with turbocompounding (electric motor control technology).
i. A 50 percent reduction in energy intensity is assumed relative to the 1980 U.S. average value of 3.8 megajoules per person-kilometer for air passenger travel, owing to various improvements.
j. The assumed energy intensity is one-third less than the simple average today in Sweden for single unit trucks (1.26 megajoules per tonne-kilometer) and combination trucks (0.76 megajoules per tonne-kilometer), to take into account improvements owing to use of adiabatic diesels with turbocompounding.
k. The average energy intensity for electric rail in Sweden, with an average load of 300 tonnes and an average load factor of about 40 percent.
l. A 40 percent reduction in fuel intensity is assumed, reflecting such innovations as the adiabatic diesel and turbocompounding.
m. Assuming an energy intensity of 3.56 gigajoules of fuel and 0.40 gigajoules of electricity per tonne, the average for Sweden in 1983.
n. Assuming an energy intensity of 84 gigajoules per tonne of fuel (the U.S. average in 1978) and 36 gigajoules of electricity, the requirements for the Alcoa process now being developed.
o. Assuming an energy intensity of 7.3 gigajoules of fuel and 3.2 gigajoules of electricity per tonne, the average for 1977 Swedish designs.
p. Assuming an energy intensity of 44 gigajoules of fuel per tonne of nitrogen in ammonia, the value with steam reforming of natural gas in a new fertilizer plant.
q. Assuming a 25 percent reduction in energy intensity, owing to innovations such as the use of advanced diesel engines. WE/JANZ stands for Western Europe, Japan, Australia, New Zealand, and South Africa.

counts for 22 percent of total energy use in Brazil, 58 percent in India, and 87 percent in Tanzania, but it accounts for only 8 percent of total energy use in the 1-kW scenario, and in absolute terms residential energy use is far less than at present for each of these countries. *(See Figure 28.)* In contrast, although the industrial sector at present accounts for only 37, 28, and 4 percent of total energy use in Brazil, India, and Tanzania, respectively, it accounts for 56 percent of total energy in the 1-kW scenario and involves more energy use per capita than in these countries at present. *(See Figure 28.)* In a sense, modernizing residential energy use frees up an enormous amount of energy that can be used to support industrial growth.

Our thought experiment is not intended to establish amenity-level targets for developing countries or dates to meet them. Rather, our

Table 22. Final Energy Use Scenario for a Hypothetical Developing Country in a Warm Climate, with Amenities (Except for Space Heating) Comparable to Those in the WE/JANZ[a] Region in the 1970s, but with Currently Best Available or Advanced Energy Utilization Technologies

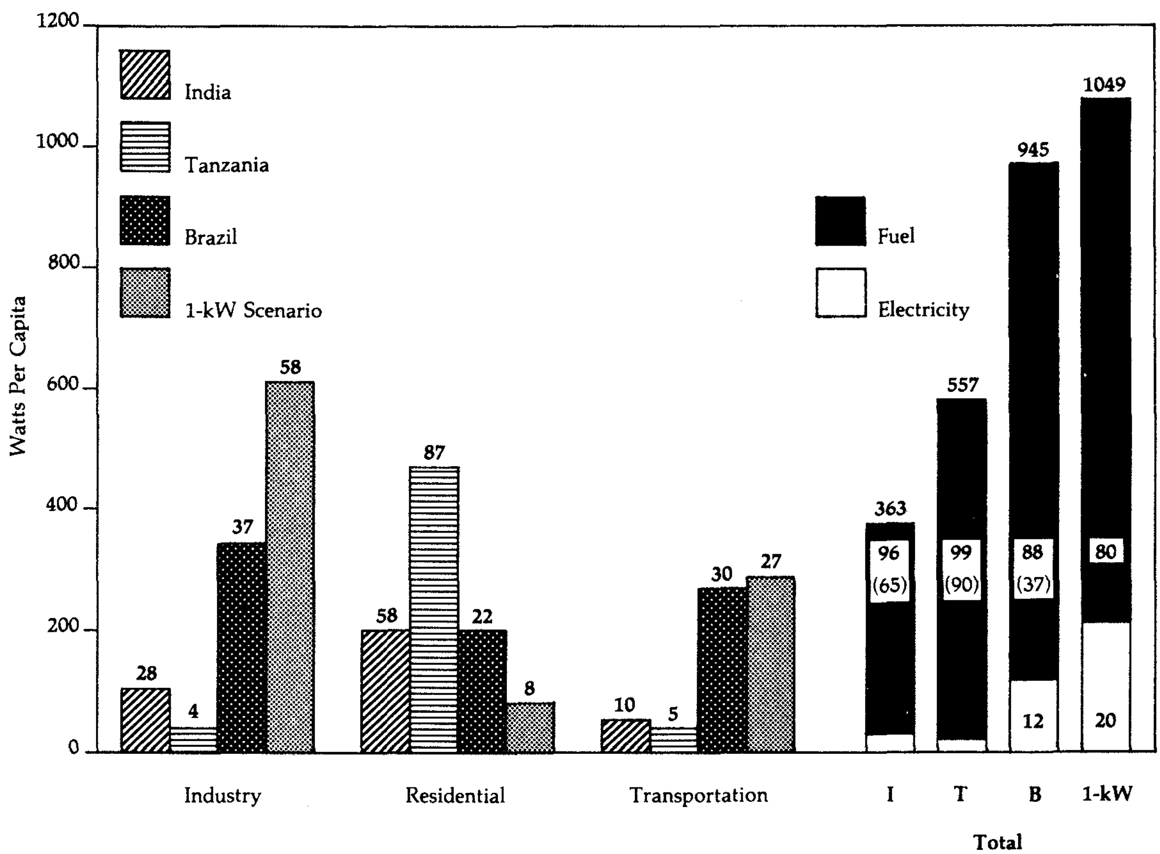
Activity	**Electricity**	**Fuel**	**Total**
	Average Rate of Energy Use (Watts per capita)		
Residential			
Cooking		34	
Hot Water	29.0		
Refrigeration	13.5		
Lights	3.8		
TV	3.1		
Clothes Washer	2.1		
Subtotal	51	34	85
Commercial	22		22
Transportation			
Automobiles		107	
Intercity Bus		26	
Passenger Train	4.5	32	
Urban Mass Transit	2.0	8	
Air Travel		21	
Truck Freight		32	
Rail Freight	5		
Water Freight (Including Bunkers)		50	
Subtotal	12	276	288
Manufacturing			
Raw Steel	28	77	
Cement	6	54	
Primary Aluminum	11	26	
Paper and Paperboard	11	24	
Nitrogenous Fertilizer		36	
Other[b]	65	212	
Subtotal[c]	121	429	550
Agriculture	4	41	45
Mining, Construction		59	59
Total	210	839	1049

a. WE/JANZ stands for Western Europe, Japan, Australia, New Zealand, and South Africa. The activity levels are those indicated in Table 20 and the energy intensities are those given in Table 21.

b. This is the residual difference between the manufacturing total and the sum for the manufacturing subsectors identified explicitly.

c. It has been estimated that at Sweden's 1975 level of gross domestic product, final energy demand in manufacturing would have been 1.0 kilowatt (half the actual value) had advanced technology been used [P. Steen, et al., *Energy—For What and How Much?* (Stockholm: Liber Forlag, 1981). In Swedish.]. The value assumed here is 45 percent less, because the average per capita gross domestic product was 45 percent less for Western Europe than for Sweden in 1975. In addition, 22 percent of final manufacturing energy use is assumed to be electricity, the Swedish value for 1975.

Figure 28. Final Energy Use Per Capita by Sector and Energy Carrier, For India in 1978, Tanzania in 1981, Brazil in 1982, and the 1-Kilowatt Scenario Summarized in Table 22



For the three sets of columns on the left, the numbers at the top are the sectoral shares in percent of total final energy use. For the four columns on the right (showing total final energy use per capita for India [I], Tanzania [T], Brazil [B], and the 1-kW scenario), the numbers at the top are the total final energy use per capita, and the numbers on the columns are the carrier shares in percent. The numbers in parenthesis on these columns give the noncommercial energy share of total final energy use in percent.

Source: For India, A.K.N. Reddy, "An End-Use Methodology for Development-Oriented Energy Planning in Developing Countries, With India as a Case Study," PU/CEES 181 (Center for Energy and Environmental Studies, Princeton University, Princeton, New Jersey, 1985). For Tanzania, M.J. Mwandosya and M.L.P. Luhanga, "Energy Use Patterns in Tanzania," *Ambio*, vol. 14, no. 4-5, (1985): 237-241. For Brazil, Republica Federativa do Brasil Ministerio das Minas e Energia, *Balanco Energetico National* (Brasilia, Brasil: 1983).

purpose is to show that it is possible to achieve a standard of living in developing countries at any level along a continuum from the present one up to the level of Western Europe in the 1970s, without greatly increasing average per capita energy use above the present level, *if* modern energy carriers and energy efficiency are emphasized as economic development proceeds. On the basis of such considerations, we assumed for our global energy scenario an average per capita level of final energy use of 1 kW for developing countries in 2020. *(See Figure 9.)*

As in the case of our scenario for the industrialized world, this scenario is not a prediction. But it is consistent with plausible values of future energy prices, income elasticities, and price elasticities associated with major increases in living standards in developing countries to the year 2020. *(See Appendix.)*

Implementing end-use-oriented energy strategies in developing countries will not be easy. Large amounts of capital will be required to bring about a shift to modern energy carriers and efficient end-use technologies. But our analysis indicates that for a wide range of activities it would be less costly to provide energy services using more efficient end-use technologies than to provide the same services with conventional less-efficient end-use technologies and increased energy supplies.

Energy can become an instrument of development instead of a brake, as it so often is today.

Most important, end-use-oriented energy strategies are compatible with the achievement of broad development goals. With emphasis on modern energy carriers and energy-efficient end-use technologies, it becomes possible to satisfy basic human needs, to expand the industrial infrastructure radically, and allow major improvements in living standards beyond the satisfaction of basic needs. Although energy alone will not produce these results, it can become *an instrument of development* instead of a brake, as it so often is today.

V. Changing the Political Economy of Energy

The long-term energy outlook would be far more hopeful than conventional projections suggest if emphasis in energy planning shifted from expanding supply to improving energy use, as described in Chapter IV. The costs of providing energy services would be lower, freeing up economic resources. North-South tensions would be eased by the more equitable use of global resources that would result. In developing countries, living standards could be increased considerably beyond subsistence in the next several decades without energy supply constraints. Finally, end-use energy strategies would permit considerable flexibility in the choice of energy supplies, making it possible to mitigate the global problems posed by increased use of oil, fossil fuels generally, and nuclear power. Yet such end-use energy strategies are probably not feasible unless government intervenes in the market.

How much market intervention would be needed to implement end-use energy strategies? The difference between more conventional projections and our scenario should not be taken as a measure of the effort required to shift course. *(See Figures 9 and 11.)* Conventional projections have not adequately accounted for structural shifts in industrialized market countries, so that even with no new interventions in the market future energy demand would grow more slowly than these projections indicate.[51] In addition, many new energy-efficient technologies, especially those offering benefits beyond energy savings, will be adopted without market intervention. Then too, many technologies even more efficient than those considered in our analysis will come to market in the decades ahead. (Most of the technologies on which this analysis is based emerged only in the last few years.) In fact, our end-use-oriented energy scenario for the year 2020 is consistent with plausible values of income and energy price elasticities and energy prices not much higher than those at present, if complemented by public policies adequate to induce economy-wide energy efficiency improvements at average rates of the order of one-half percent per year. *(See Appendix.)* Thus, although new public policy initiatives are needed to bring about an energy future like the one described here, the effort required would not be Herculean.

Although this chapter offers general guidelines for energy-policy-making and includes some specific policy proposals, it stops short of providing a blueprint for implementing end-use energy strategies. Specific policies must be tailored to the cultural and political conditions of different countries. In addition, experience with policies to promote innovation in energy end-use is still too limited to show clearly what the best approaches are. Moreover, end-use-oriented energy policies should be continually changed over time, not only to make the adjustments suggested by experience but also to reflect changing needs. The use of energy throughout the economy is determined by a combination of user preferences, incomes, the resourcefulness and technical know-how of those who produce and sell energy-using technologies and related services, and other factors. Further, user preferences as well as the technological and institutional opportunities for satisfying consumer needs are varied and ever changing. In short, patterns of energy use depend on decisions by large numbers of consumers, each continually confronted with scores of energy-related decisions. This pattern of decision-making is far more complex than that for the production of energy, which generally involves only a few energy forms and a relatively small number of producers. Nonetheless, policy-makers must try promising new approaches, assess how well different approaches work in different situations, and make continual adjustments in light of experience.

Patterns of energy use depend on decisions by large numbers of consumers, each continually confronted with scores of energy-related decisions. In contrast, the production of energy generally involves only a few energy forms and a relatively small number of producers.

The Role of Markets in End-Use Energy Strategies

Market Shortcomings. Despite the economic attractiveness of end-use energy strategies, the market cannot be relied on to promote them because of (1) existing policies that further the expansion of energy supply *(market biases)*, (2) the reluctance of many consumers to make cost-justified energy-saving investments *(market friction)*, and (3) the inherent inability of markets to meet the challenges of poverty, the external social costs of energy production and use, and the welfare of future generations *(market failings)*.

New public sector interventions are needed partly because past interventions have biased the market in favor of energy supply expansion. Historically, either energy producers have been subsidized or prices have been held down to benefit consumers.

Government support for energy producers has come in various, sometimes ingenious, forms: tax breaks—including depletion allowances, intangible cost write-offs, accelerated depreciation, and investment tax credits—as well as a variety of other subsidies, hidden and overt. For example, almost every industrialized country has subsidized the development and commercialization of nuclear power, certain aspects of nuclear plant operations, and even the export of nuclear technology.

One problem with energy supply subsidies is that they keep energy prices below the true long-run marginal costs of energy supplies and thus encourage economically inefficient consumption. A more serious problem is that such subsidies make energy supply investments especially attractive to investors, making capital for other investments scarcer. Subsidies to energy producers may not even increase energy production. Indeed, unless they are directed to research activities having no prospect of direct commercial payoff, energy supply subsidies tend to decrease net energy yields because increased energy production will be more than offset by increases in the energy opportunity costs of the non-energy inputs induced by the subsidy.[52]

Governments have also set energy prices below market-clearing levels for certain classes of consumers—to promote particular patterns of economic growth or, as in the 1970s, to cushion the impacts of market price increases on certain consumer groups or on the economy generally. The prices of kerosene or liquid petroleum gas in many developing countries are controlled to protect the poor, who need these fuels for lighting or cooking. In many countries, energy prices have been kept especially low for energy-intensive industries, such as those involving the production of primary aluminum or chemicals. In recent years, developing countries have often used such energy price subsidies to promote a pattern of development that emphasizes the export of processed basic materials.

It is necessary to control prices in markets where suppliers have monopolies, such as electricity markets. However, electricity prices in many parts of the world are set below economically efficient long-run marginal costs and instead are based on average costs (i.e., the electricity price equals the cost of production divided by the total electricity sales, with rates for different consumer groups adjusted to reflect differences in cost of service). In a number of developing countries, revenues don't even cover total costs.

Overall, efforts to subsidize energy producers and consumers have promoted economic inefficiency and slowed adjustment to the new economic realities of energy. Very often these inefficiencies extend far beyond the targeted sectors. In India, for example, where the price of kerosene was kept low to protect the poor, the subsidy had to be extended to diesel fuel as well in order to keep diesel fuel consumers from switching to kerosene (which can be used in diesel engines) and thus diverting kerosene supplies from the poor. Extending the subsidy to diesel fuel created excess demand for diesel-based truck freight, heightening the country's dependency on imported oil.[53]

Short-run oil price fluctuations notwithstanding, the era of cheap energy is over. It ended in 1973, and government subsidies and price controls only put off the day when energy producers and users adjust to this unpleasant reality.

Market friction also inhibits cost-effective investments in energy-efficiency improvements. If consumers were economically efficient, they would seek to minimize life-cycle costs in their purchases of energy-using equipment—that is, they would choose for space heating, refrigeration, cooking, travel, or another energy service those end-use technologies for which the dollar savings from reduced energy costs represent a return on the required additional investment comparable to the return from alternative investment opportunities. In practice, though, many energy consumers invest in energy-efficiency improvements only if they can be assured of much higher returns. To put it more simply, consumers typically must be assured of payback periods of two or three years or less[54]—far shorter than the 10-to 15-year payback periods typical of investments in new energy supplies.

Efforts to subsidize energy producers and consumers have promoted economic inefficiency and slowed adjustment to the new economic realities of energy.

Why aren't consumers more willing to invest in energy efficiency? Information about the potential cost savings from investments in energy efficiency is often inadequate or unreliable, acquiring the right information and making the appropriate investment is a "hassle," capital to finance such investments may be scarce, and future energy prices may be uncertain. In addition, if the buyers of energy-using devices are not also the ones who will use the devices, they may be reluctant to make the extra investments in energy efficiency. For example, landlords or builders who purchase appliances, furnaces, and air conditioners rarely take much interest in the operating costs that tenants or homebuyers will be shouldering.

Like the market biases discussed above, these forms of market friction boost energy demand levels higher than they would be if life-cycle costs were minimized, and thus they draw capital to the expansion of energy supply from other purposes.

Even a properly operating market cannot redress poverty, which involves considerations of equity, not economic efficiency. The best that can be expected from an efficient market is relatively rapid economic growth. It has often been argued that while the rich get richer with more rapid growth, the poor get richer too. But the "trickle down" approach to development has not effectively addressed poverty in developing countries. In industrialized countries, high energy prices have induced middle-and upper-income households to become more energy efficient, but they also created severe economic hardships for people too poor to invest in more efficient cars and appliances or in thermally tighter homes.

Decisions made in free markets also do not reflect social costs that are not accounted for in market prices. These so-called external social costs include: the loss of self-reliance in market power and in foreign policy because of overdependence on oil imports; the risk of war, even nuclear war, as a consequence of the dangerous dependence of the industrialized market economies on Middle East oil; the risk of nuclear weapons proliferation associated with the availability of weapons-usable materials from nuclear power fuel cycles; and the risk of climatic change associated with the atmospheric build-up of carbon dioxide from fossil fuel combustion.

Finally, the market does not look after the interests of future generations—witness the private sector's lack of interest in basic and applied research, for which the potential payback extends far beyond business planning horizons. Privately funded research and development (R&D) is concentrated, instead, largely on improvements in existing products and processes, which promise near-term benefits. Private firms also cannot capture the benefits of R&D that provides only generic information. In addition, private firms have little incentive to pursue research and development in areas in which much of the potential payoff involves broad social benefits—such as research aimed at understanding the problems of the poor and how these problems might be alleviated or research on indoor air pollution and the side effects of energy-efficiency improvements.

The Importance of the Market in Implementing End-Use Strategies. Although market intervention is needed to implement end-use energy strategies, market mechanisms need not be abandoned. To the contrary, a properly functioning market has a far more important role in implementing end-use energy strategies than in executing conventional energy strategies.

A properly functioning market has a far more important role in implementing end-use energy strategies than in executing conventional energy strategies.

The complexities of energy end-use decision-making generally can be dealt with far more effectively by those who know exactly what they need and can afford (that is, the buyers) and by those who know what the energy-using devices cost to produce (the sellers) than by bureaucracies. Bureaucracies are notoriously ineffectual in keeping track of the needs and preferences of a multitude of users and in replacing buyers' and sellers' free-wheeling interactions with their own procedures and rules—witness the emergence of black markets whenever bureaucracies allocate resources. Accordingly, policy should be aimed at improving the market's ability to allocate resources relating to energy end-use and intervening more actively only where the market mechanism is inherently weak or incapable of implementing social goals. Far more important than any specific detail in these initiatives is that government create a favorable environment for energy-efficiency improvements.

Market Intervention in the Present Political Climate. On the surface, at least, the present political climate does not seem favorable to interventionist policies. The political pendulum has swung away from government intervention, especially in the United States and Great Britain. But even in a capitalist country such as Japan, with a long tradition of government guidance of the economy, and in such socialist countries as China and Hungary, there has been movement toward *laissez faire* policies. Democratic socialists throughout Western Europe are rethinking their policy agendas and seeking alternatives to nationalization, price controls, the expansion of the welfare state, and other approaches. In many parts of the world, terms such as "privatization," "deregulation," "fiscal belt-tightening," and "free market economics" are currently fashionable.

To put these observations in perspective, a few aspects of the current political swing need to be noted. Why has it occurred? Certainly, three of the many factors involved stand out. First, there has been widespread disillusionment with the poor performance of publicly owned enterprises. Second, many people are worried about rising government costs and are wary of the measures governments have taken to manage them (either raising taxes or printing money). Third, fiscal austerity and *laissez faire* policies popular in the market-oriented countries of the North have been imposed on many developing countries by the International Monetary Fund and international banks as conditions of obtaining more credit.

Still, the political pendulum has a way of swinging back. All through the 1920s, for example, it was swinging toward *laissez faire* policies and austerity; in 1929, it headed back swiftly. It is impossible to say exactly what impetus may change policy direction. Perhaps it will be another oil price shock sometime in the 1990s. Perhaps it will be a combination of factors. In many industrialized countries, chronic unemployment and slow productivity growth persist. In addition, the manufactured goods exported from developing countries are becoming increasingly competitive in the markets of industrialized countries. These factors may combine with high oil prices to induce economic stagnation or worse. Under such circumstances, the public sector would have to intervene to improve economic performance, and policies for stimulating improved energy efficiency would then logically come into play.

And, of course, one important reason for intervening in the market is to remove the biases arising from past interventions, thereby strengthening the market mechanism in energy decision-making, a goal that should be widely shared even in the present political climate.

Promoting More Efficient Use of Commercial Energy

Given the need to eliminate market biases, reduce market friction, and compensate for inherent market failings, what are the elements on an end-use energy policy needed to promote more efficient use of commercial energy? In addressing this question, we focussed on the market-oriented industrialized countries, although much of our analysis is also relevant to the modern sectors of market-oriented developing countries.

Eliminating Energy Supply Subsidies. Despite the economic distortions they may cause, existing subsidies to energy supply industries are often considered too entrenched to remove. Consequently, some "political realists" have often proposed compensating for their ill effects by extending similar subsidies for investments in energy-efficiency improvements and solar energy.

Such alternative subsidies, however, also pose problems. It is generally difficult to remedy one market distortion with another.

The compensating measure will tend to offset only partially the effects of the original distortion, and it may have unintended, undesirable side effects. Moreover, subsidies are not needed to make competitive a wide range of technologies relevant to end-use energy strategies.

A more appropriate policy would be to challenge the conventional political wisdom and eliminate existing subsidies for energy supplies while simultaneously implementing policies that promote minimal life-cycle costs in market decisions relating to energy. In general, energy subsidies should be used only to solve the problems the market cannot solve—for example, to alleviate the energy problems of the poor and promote research and development.

In principle, current efforts to promote fiscal austerity and free-market economics should work to eliminate energy supply subsidies, but even in this political climate, doing so will not be easy. For example, the historic tax legislation passed by the U.S. Congress in late 1986 preserves major subsidies long enjoyed by the U.S. oil industry, even though the legislation was designed to eliminate distorting subsidies and promote fairness.

Rationalizing Energy Prices. Economic efficiency would be enhanced and consumers' incentives to use energy efficiently would be increased if energy prices reflected the high costs of new energy supplies—that is, if controls designed to keep energy prices artificially low were eliminated and utility rate structures were redesigned to sensitize consumers to the costs of new supplies.

However, policies enacted to bring energy prices in line with long-run marginal costs must be carried out in conjunction with policies that address the problems that the original pricing policies were designed to solve. For this reason, and because entrenched interests may fiercely oppose price rationalization, it may be necessary to phase in price reforms slowly.

Improving the Flow of Information. Lack of information about energy-saving opportunities impedes investments in cost-effective energy-efficiency improvements. Government can help improve market performance by enhancing the flow of such information to consumers.

One option is making generic information available through "energy extension services," akin to the agricultural extension services that have been so successful in facilitating the transfer of productivity-enhancing technologies from the laboratory to the farmers' fields in the industrialized countries.

Energy utilities might also be required to offer advice that reflects customers' unique needs, as determined by energy audits. Most large gas and electric utilities in the United States are required to offer such audits to residential customers. The challenge is to ensure that customers receive accurate and useful information. Measurements made in instrumented audits can be far more reliable than paper-and-pencil audits, but such information is also much more costly to obtain. However, these higher costs can often be justified if audits are carried out in conjunction with corrective actions, as in the case of the "house doctor" concept developed in the United States. *(See Chapter IV.)* The success of any audit program depends on the reward system; a law simply requiring utilities to conduct audits without making it profitable for them to provide good ones probably won't succeed.

Another way to improve the flow of information would be to require that certain energy-intensive products be labeled to indicate their energy performance at the time of sale. Labeling is useful for products whose energy performance is readily measurable, relatively unambiguous, and easily understood. Candidates for such labels are automobiles, various household appliances, and even whole houses.

Targeting Energy Performance. Many of the same energy-intensive products eligible for mandatory labeling are also candidates for energy performance targets. Such targets help protect—among others—those energy users who are stuck with energy-using equipment purchased by builders or landlords. They also give manufacturers signals, clearer and steadier than those of fluctuating prices, that energy efficiency matters to both consumers and society as a whole.

In some cases, such targets offer major social benefits that market forces alone cannot bring about. For example, compare the private and the social benefits of improving automotive fuel economy. With today's technology, the fuel economy of automobiles could be improved from the current global average of 18 mpg (13 liters per 100 kilometers) to 80 mpg (3 lhk) or better. *(See Chapter IV.)* Although the total cost per mile or kilometer of owning and operating a car declines rapidly with improved fuel economy up to about 30 mpg (8 lhk), it remains roughly constant at higher fuel economies. *(See Figure 26.)* The consumer has no incentive to seek fuel economies better than about 30 mpg (8 lhk) because savings owing to reduced fuel requirements are just about offset by the higher first costs for fuel economy improvements and because at high fuel economy levels, fuel accounts for such a small fraction of the total cost of owning and operating a car. In other words, consumers would not be any worse off with cars of higher fuel economy, but they wouldn't be any better off either.

Consumers would not be any better or worse off with cars of higher fuel economy, but society would be much better off.

In contrast, society would be much better off if consumers had more efficient cars. If oil imports were lower, the world oil price would probably be lower too. In addition, the world would likely be more secure, with a smaller likelihood of conflict over access to Middle East oil. The prospect of generating such enormous social benefits without burdening the consumer provides a powerful rationale for public sector intervention to promote high fuel economy in cars.

Various policy instruments could be used to bring about market shifts to high-efficiency products. Energy performance might be regulated to promote high automotive fuel economy or high-efficiency appliances. Taxes might accomplish much of the same goal; for example, devices performing worse than the average for new devices of their kind might be taxed at the time of purchase, with the penalty increasing in proportion to expected extra life-cycle energy requirements. Utilities might be required to offer rebates to customers who buy household appliances that are more efficient than the average for new appliances, with the rebates increasing proportionally with the expected energy savings. To the extent that such rebates allow a utility to defer investments in more costly new energy supplies, the consumer, the utility, and all the utility's rate-payers would benefit. A growing number of U.S. utilities offer such rebates for certain appliances.

Stabilizing Consumer Oil Prices. The market cannot be relied on for regulating the world oil price. The world oil market has been characterized by wildly fluctuating prices with alternating periods of shortage and glut. *(See Figure 1.)* The onset of a glut following each price shock gives investors the misleading impression that the oil crisis is over and encourages increased oil consumption, setting the stage for still another shock. Moreover, the periods of oversupply, as we have seen in the mid-1980s, diminish the sense of urgency needed to induce oil importers to reduce their long-run vulnerability to supply disruptions. In general, uncertainties about future oil prices discourage investments in energy efficiency.

Efforts by major oil importers to make specific end-use technologies (such as the automobile) more energy-efficient could be successful initially in driving oil imports down and thus forestalling a rise in the world oil prices. However, by exerting downward pressure on the world oil prices, they could stimulate oil consumption in other areas. *(See, for example, Figure 10.)*

What is also needed is more stable consumer oil prices. Stability could be achieved with a variable tariff on oil imports or a tax on oil products that shields consumers from the vicissitudes of the world oil market. Ideally, such a tariff or tax should keep consumer oil prices constant or slowly rising in time, so it would have to be adjusted continually for real changes in the world oil price and for general inflation.

Stable or slowly rising consumer oil prices would make the economic environment for investments in energy efficiency and other alternatives to imported oil more predictable and thus more favorable. They would help prevent sharp upturns in the world oil price and make the world more secure.

Setting and administering such a tax or tariff would not be easy. The relative merits of tariffs and oil product taxes, the appropriate level of consumer oil prices, issues of equity, the effect on the overall economy, and other issues would have to be taken into account. So would important international issues, discussed below.

Promoting Comprehensive Energy Service Delivery. It is relatively straightforward for a consumer in an industrialized country to purchase natural gas, oil, or electricity. Well-established systems exist for making such transactions. The quantities exchanged are easy to measure, and both buyer and seller understand the values of the commodities.

Making energy-saving investments is not so simple. Marketing energy efficiency requires diagnosing the individual consumer's energy needs and finding ways to meet them in the most cost-effective manner. The consumer must be educated about the need to make energy-saving investments—difficult when the expected savings are often uncertain. Financing must often be provided for new equipment or required contract work. After-purchase performance in the field should be monitored to ascertain actual savings and the information thus acquired used to modify energy-saving strategies.

The energy price shocks of the 1970s prompted the formation of energy service companies in some countries to help industry cut energy costs. The delivery of such technical assistance to individual consumers or small businesses, however, remains haphazard at best.

One way to provide the needed assistance is to convert energy utilities into "energy service companies" that market heating, cooling, lighting, etc., much as they now market electricity or natural gas. Some U.S. electric and gas utilities already provide advice on investments in energy efficiency, arrange for contractors to carry out the necessary work, finance such investments with low- or zero-interest loans, and offer rebates to consumers who purchase energy-efficient appliances or to sellers who promote these appliances.

Accustomed to accumulating large quantities of capital, utilities are well-positioned to invest in energy efficiency. They also have the administrative structures for channeling capital to essentially all households and businesses. Through a utility's billing system, for example, customers can pay "life-cycle cost bills" instead of fuel or electric bills if they receive loans from the utility for energy-efficiency investments. Finally, utilities are in a good position to undertake such difficult tasks as the retrofitting of existing buildings with energy-efficiency improvements. For example, utilities could provide a comprehensive "one-stop retrofit service" that includes audit and post-retrofit inspection, coordination of contractor work, and long-term financing.

Of course, energy utilities won't become energy service companies until utility regulators develop publicly acceptable ways of financially rewarding them for facilitating cost-effective energy-efficiency improvements in their markets. Once they have a clear financial stake, utilities can play the role envisioned for them by Thomas Edison when he invented the incandescent bulb and proposed that utilities sell illumination, thereby giving them a financial interest in providing this service in the most cost-effective way.

In some cases, utilities can't or won't create needed energy conservation programs. For example, electric or gas utilities may not wish to offer retrofit services for oil-heated homes. Some may have so much excess capacity that they see no need to help customers use energy more efficiently. In such circumstances, government could stimulate the creation of new independent companies that would market energy-efficiency improvements by, for example, making loans or grants available to customers of such firms.

Where neither utility nor private sector efforts to market comprehensive energy conservation are feasible, local governments could assume the responsibility.

Making Capital Available for Energy Efficiency Investments. Capital for energy-efficiency investments can be made more readily available through general tax reform and through measures that direct capital resources to specific applications.

Because so much capital has been directed to energy supply investments, eliminating subsidies for new supplies should free up more capital for purposes other than energy production. The question is whether more should be done to make capital available for investments in energy efficiency. For example, should government direct capital to the steel industry to stimulate its modernization and thereby improve its energy efficiency, or should the market determine how much capital goes to the steel industry? Different market-oriented industrialized countries have different answers to these questions. Such questions of general industrial policy are too complex to consider here.

Without question, though, government intervention is needed to make capital more available to individual consumers. Mortgage laws, for example, could be changed so that the financial institutions that determine the size of the allowable mortgage consider the energy-efficient household's increased ability to repay a loan. Special funds could be established by government to finance qualifying energy-efficiency investments. And energy utilities could be encouraged to make capital available to their customers for such purposes.

Simply making more capital available at market interest rates in conjunction with improved overall delivery of energy services may often be more important than providing capital at subsidized rates.

Simply making more capital available at market interest rates in conjunction with improved overall delivery of energy services may often be more important than providing capital at subsidized rates. Capital subsidies should be used only where less costly alternatives cannot work—such as investments in energy efficiency for the poor.

Assisting the Poor. Middle- and upper-income households in industrialized countries can adjust to higher energy prices by insulating their homes, buying more fuel-efficient new cars, and the like. But many poor people with little or no capital resources or credit live in poorly insulated, drafty houses built before the oil crises and depend for transportation on gas-guzzling cars discarded by the better-off.

The burdens of high energy costs would be reduced for the poor by implementation of some general energy-efficiency policies, such as energy performance standards for appliances and automobiles. But these measures alone are not likely to prevent economic hardship. Moreover, policies aimed at raising energy prices to reflect the long-run marginal costs of production will increase the suffering of the poor.

The needs of the poor have often been cited as reasons for keeping energy prices low. However, an economically efficient pricing system complemented by special programs to help the poor is far preferable to economically inefficient systems of price controls to protect the poor.

In adjusting utility rates to reflect long-run marginal costs, one way to ease the burden on the poor would be to keep the overall revenue generation rate fixed, while allowing the rate charged for energy to vary with consumption—with rates below the present price for low levels of consumption to full marginal costs for high consumption levels. Alternatively, rates could be raised across the board to marginal cost levels, with compensating measures to protect the poor. When rates are raised to marginal costs, utilities would realize windfall profits proportional to the difference between the marginal and average costs. These profits should be taxed away or returned to consumers in ways not directly related to energy consumption. In either case, some of the excess revenues could be allocated to the poor.

Similarly, if a new tax is levied on energy, the regressive nature of the tax might be countered by using the resulting revenues creatively. They might be used to offset some regressive tax (such as the Social Security tax in the United States[55]) or to help the poor directly.

Some kind of direct subsidy is generally needed to help poor households cope with high energy costs. But what kind? In the United States, the federal government provides modest assistance to help the poor pay fuel bills and even more modest assistance to help winterize the homes of the poor. But more ambitious programs are called for. Assistance in paying fuel bills helps reduce immediate hardship, but the greatest need is for *investments* to reduce fuel bills, especially for space heating. Because many poor people live in inferior housing, energy-efficiency improvements should be coordinated with programs aimed at more general improvement of this housing.[56] Large one-time investment subsidies to the poor for retrofitting their homes would be economically more efficient than continually subsidizing their fuel bills, and they would not be as demoralizing as continued dependence on assistance programs.

In the long run, changes in the structure of employment induced by implementing an energy-efficiency strategy may be more important to low-income people in industrialized countries than any changes they experience as consumers. Almost all econometric studies show that labor will be substituted for energy as energy prices rise,[57] so that energy taxes should generate employment. In addition, economic production associated with improving energy efficiency and providing products low in energy intensity tends to involve higher employment levels per dollar of economic activity than the production that is replaced.[58] Employment associated with end-use efficiency would also tend to be less specialized, and increasing less specialized employment could reduce structural unemployment—one of the most intractable poverty-related problems confronting industrialized countries.

Promoting Research and Development on Energy End-Uses. Although major improvements in energy efficiency can be made with end-use technologies that are already commercially available, considerable further improvements could be realized with appropriate R&D.

The era of energy-demand consciousness is barely a decade old, and energy-efficient end-use technology is still in its infancy. R&D exploring opportunities for improvements in energy efficiency will help make energy efficiency a design criterion in the process of technological innovation, in which the new processes and products chosen for commercialization tend to be those that offer simultaneous improvement of several characteristics.

Research is also needed on the social aspects of energy end uses—to improve techniques for evaluating conservation programs, to provide a better understanding of how to motivate consumers to base energy decisions on life-cycle costs, and to clarify the energy problems of the poor and how to meet their needs effectively.

Government should help create an economic climate conducive to such private sector R&D and should sponsor promising R&D activities when private efforts fall short. The policies outlined here for improving the climate for investments in energy-efficiency improvement—especially eliminating subsidies to the energy supply industries and adjusting prices to reflect marginal costs—would by themselves tend to create an economic climate conducive to the pursuit of energy-saving innovations by the private sector. In addition, tax laws might be modified to give favorable treatment to R&D.

In general, strong government support for R&D is needed when risks are too high, benefits too diffuse, and payback too long to justify strong private support. Specifically, public support is needed for basic research (scientific investigation aimed at expanding scientific understanding), applied research (generic research aimed at applying scientific methods to solving technical problems), research on external costs (such as indoor air pollution), and technology assessment (including monitoring and evaluating the field performance of end-use technologies).

Despite the importance to end-use energy strategies of research on the technical and social aspects of energy end uses, such research is only a minor part of government-sponsored R&D. In 1981, only about 6 percent of government R&D funds in the International Energy Agency countries were committed to energy conservation—about one tenth the amount spent on nuclear energy. *(See Table 23.)* By 1983, overall government R&D expenditures and government expenditures on energy conservation had declined 20 percent while expenditures on nuclear energy remained at the 1981 level. In the United States, R&D expenditures on energy conservation were sharply reduced under the Reagan administration while those for nuclear energy remained largely unchanged. Adopting end-use energy strategies will thus require a major restructuring of energy R&D.

Creating and Maintaining Energy End-Use Data Bases. To set priorities for end-use energy strategies, policy-makers need to understand how the present end-use system works and how trends in particular end-use activities shape aggregate energy demand. Planners' information needs include the energy requirements and consumer prices of various energy forms, the energy needs and expenditures of each economic sector and subsector, patterns of energy consumption disaggregated by end-uses, etc. Planners also need demographic and economic data. To meet these needs, detailed and highly disaggregated energy demand-supply data bases should be developed and maintained.

Keeping Score on Conservation Programs. As noted, the complexity and ever-changing character of energy-use patterns make it difficult to predict the best comprehensive end-use strategy. In implementing such strategies, policy-makers will have to try promising new approaches, monitor and assess the efficacy of new programs, and make continual adjustments in light of successes and failures.

To this end, fast and reliable "scorekeeping" techniques are needed for measuring the effectiveness of particular conservation programs

Table 23. Distribution of 1981 and 1983 Government Energy R&D Budgets in IEA countries (in percent).

	1981	**1983**
Conservation	5.9	5.9
Oil and Gas	3.6	4.5
Coal	14.1	8.0
Nuclear (Nonbreeder)	27.8	36.6
Advanced Nuclear	26.0	31.2
New Energy Sources (Solar, Wind, Ocean, Biomass, Geothermal)	12.9	8.8
Other Sources and New Vectors	0.7	0.4
Supporting Technologies	9.1	4.6
Total	100	100
Total Expenditure at *Current* Prices (million dollars)	8,356	6,632

Sources: For 1981: Organisation for Economic Co-operation and Development, "Energy Research and Development and Demonstration in the IEA Countries: 1981 Review of National Programmes," Paris, 1982. For 1983: Organisation for Economic Co-operation and Development, "Energy Research and Development and Demonstration in the IEA Countries: 1983 Review of National Programmes," Paris, 1984.

and understanding the reasons for successes and failures.[59] Timely feedback on the energy savings actually realized in ongoing programs would enable planners to improve these programs and would also help protect consumers against fraudulent or incompetent energy-service firms.

Energy and Economic Development

In developing countries, energy systems command such large shares of development resources that energy policy cannot be considered apart from development policy generally. Energy policy determines not only the kinds and amounts of energy sources developed but also the allocation of energy supplies among sectors and consumer groups. *(See Chapter IV and Energy for Development[60].)*

Energy Efficiency in the Modern Sectors of Developing Countries. Most opportunities for more efficient energy use in industrialized countries are also relevant to the modern sectors of developing countries. Because energy efficiency investments often lead to reduced overall capital requirements for providing energy services, such investments can be even more important to developing countries, where capital is scarce. *(See Figure 25.)*

However, energy-efficiency strategies may be more difficult to implement in developing countries. One reason for this judgment is that not all policy instruments that can be used in industrialized countries are practical for the developing country situation. For example, the rebate programs used by some U.S. utilities to promote energy-efficient appliances in households would not work where there are no effective mechanisms for delivering rebates to the poor.

In addition, price-reform efforts in developing countries must be accompanied by compensating efforts to ease the burden of higher energy prices on the poor. For example, in countries where the kerosene price is kept low to protect the poor, the prices of kerosene and diesel fuels should be increased only in conjunction with programs that give the poor alternatives to kerosene for lighting (for example, rural electrification) and cooking (say, biogas or producer gas).

Developing countries also face special policy issues in introducing new energy-efficient technologies. If these technologies must be imported, the country must decide whether to spend precious foreign exchange on them. A proper evaluation of the foreign exchange issue, however, should cover the entire energy system—improved end-use technology and energy-supply technology—because the increase in foreign exchange for a more efficient device is often more than offset by a reduction in foreign exchange requirements for new energy supplies.

Ultimately, of course, the domestic manufacture of energy-efficient technology would be desirable in many countries, and the investment and infrastructure requirements for building that capability must be understood. Some countries are already developing such capabilities. In India, for example, typical five-passenger cars in use get 21 to 24 mpg (10 to 11 lhk), but typical new domestically manufactured cars have fuel economies of about 40 mpg (6 lhk). There is strong evidence that Brazilian manufacturers could produce energy-efficient refrigerators, lighting systems, heat pumps, motors, and motor control devices in just a few years, if there were sufficient demand for such products.[61]

These examples, of course, are not surprising in view of the fact that exotic technologies are typically not required to improve energy-using devices dramatically. The key to introducing such new products is convincing manufacturers that there would be adequate markets. Thus, utility and government programs to promote the development of such markets through procurement, loan programs, and the like are especially important.

Planners in developing countries face a new set of challenges in implementing "technological leapfrogging" strategies. Developing countries should not be content to adopt energy-producing and energy-using technologies from the industrialized countries, which often will not be matched to local human and natural resources or be compatible with economic expansion in the new era of higher world energy prices. Instead, developing countries should continually be seeking new technological opportunities that could lead to improved productivity, consistent with available resources, environmental goals, and security concerns. Adopting such new technologies before they are proven in the industrialized countries entails greater technological risk-taking than most developing countries are accustomed to. Although any action should be preceeded by a careful evaluation of the potential benefits, prudent risk-taking can enhance long-term development prospects.

Energy and Basic Human Needs. As pointed out here, the structure of the energy demand-and-supply system depends on the approach taken to alleviating poverty, and an especially promising approach is to allocate energy and other resources directly to meeting basic human needs for nutrition, shelter, sanitation, clothing, health, and education.

The energy policy implications of the basic human needs approach to poverty alleviation will vary from country to country. Ascertaining these implications requires detailed data collection and close analyses of how much energy various economic activities require, which energy resources are available, and which alternative combinations of energy-supply and energy end-use technologies could be used to meet demand.

Some specific actions are widely applicable, however. Chief among them is providing energy-efficient cooking stoves. Comprehensive programs are needed, including research and development on promising new designs, field testing for actual energy savings and consumer acceptability, and promoting the diffusion and use of stoves. *(See Figure 8).* Particular attention must be given to introducing stoves in households outside the market economy.

Bringing electricity to all households should also be given high priority. In rural areas, where access to centralized electrical grids is particularly costly or impractical, decentralized power sources based on local resources e.g., producer-gas generator sets using biomass fuel should be examined closely. Because technologies for decentralized power generation are not nearly so well-established as those for centralized power, R&D on energy-efficient small-scale power sources should receive high priority.

A closely related but more general challenge is to modernize bioenergy resources by developing efficient ways to convert raw biomass into high-quality energy carriers—such as gases, liquids, processed solids, and electricity—so that scarce biomass resources can provide far more useful energy than is feasible at present.[62] Here too, major R&D efforts are required.

Finding the resources for the R&D will be challenging. Support from international aid agencies may be needed in many instances. Cooperative R&D programs mounted by groups of developing countries might sometimes be desirable. Collaboration with industrialized countries should also be considered; a promising division of labor might involve carrying out basic research (e.g., combustion, heat transfer, and the fundamentals of gasification) in industrialized countries and more applied research (aimed at designing and testing new technologies) in developing countries.[63]

Energy and Employment Generation. In evaluating the employment implications of all alternative technologies and strategies for development, planners should give particular attention to the problems posed by over-investment in basic materials-processing industries that generate few jobs. *(See Chapter IV.)* To the extent that such over-investment is the result of subsidies to producers and consumers, efforts to bring energy prices into line with long-run marginal energy costs would be especially helpful, as would tax and investment policies that do not favor such industries over others.

Assessing the appropriateness of new industrial technologies requires particular attention to the potential for employment generation. Particularly desirable are modern competitive technologies that are also employment-intensive—the Brazilian alcohol and charcoal steelmaking industries, for example.

Energy for Agriculture. Few energy needs in developing countries are as crucial as the needs for expanding agricultural production to feed a growing population. Although agricultural energy needs will expand rapidly, the absolute amounts of energy required would not necessarily be formidable with an end-use energy strategy. *(See Chapter IV.)*

Efforts to improve energy efficiency in other sectors, especially efforts to save oil in transportation, would go a long way toward making oil import requirements for agriculture affordable. Efforts to save oil in the market-oriented industrialized countries would also help by helping to keep the world oil price from rising. *(See Figure 10.)*

Efforts to modernize bioenergy would also help. Possibilities include using producer gas engines for running pump sets, vehicles, and other farm equipment and using biomass-derived liquid fuels (methanol and ethanol) in vehicles.

Political Feasibility. The energy strategy described here for developing countries is technically and economically feasible. However, adoption of this strategy would require a marked departure from the *status quo* in many countries.

Logically, energy policy should promote sustainable development, but not all those in power in developing countries hark to this logic. Not the least of required changes would be a major shift in the allocation of capital. Although the proposed effort would be partially "self-funded" in the sense that the pursuit of energy-efficiency improvements would free economic resources for other purposes, some funds would have to come from taxing the elites.

Will the elite abide such changes? Elite minorities control virtually every aspect of political and economic life in developing countries—in marked contrast to the poor and politically weak majority, dispersed in villages and crowded in metropolitan slums. And what about foreign interests? When the elite buy imported technologies, export commodities, and borrow large sums of capital, they are operating in an international economic arena dominated by the interests of the industrialized countries. These twin realities shape decision-making in developing countries.

Generally, the elite put great emphasis on big projects, such as dams and airports, and on patterns of industrialization and trade that bring those in power the material comforts available in industrialized market countries—automobiles, air conditioners, airplanes, refrigerators, and the like. As it happens, these interests coincide nicely with the interests of the major international credit and aid agencies, most of whose loans or grants cover expenses involving foreign currency. Aid money is spent primarily on technologies and consulting and engineering services from the aid-giving countries. Thus, much of the aid ends up back in the industrialized countries, increasing demand for their bulldozers, turbines, irrigation equipment, nuclear reactors, etc.

Energy policy in the developing countries has stressed large centralized energy supply projects—especially for electricity generation and transmission—and imported oil. Too often the energy needs of the poor, especially in rural areas, have been neglected. Hydroelectric projects, nuclear power plants, and refineries have attracted far more attention and capital than, say, the humble wood stove on which so many depend for cooking and heating and in which so much energy is wasted.

Yet, it is not far-fetched to expect the elites in the developing world to support development along the lines described here. Poverty is so dire and pervasive that neglecting it or relying on some variation of the "trickle down" approach is to risk social upheaval. There is, of course, a political risk in providing poor people access to basic economic and educational resources, but this risk pales beside that of the political instability inherent in festering poverty. Thus, it is in the long-term self-interest of the elites to identify and support effective programs for eradicating poverty.

Moreover, the outlook for sustained economic growth in many developing countries through business as usual is not promising. Continued heavy emphasis on exports, which has largely shaped the present mix of economic production in the developing countries, may cause serious problems in the years ahead. Although the shift from producing commodities for export to producing processed basic materials has helped protect the economies of developing countries from the vicissitudes of world commodity markets, the outlook for the export of manufactured goods to the rich industrialized countries is clouded.

The developing countries are already beginning to feel the protectionist measures by industrialized countries bent on preventing the further loss of jobs in basic industries. Unfortunately, the problem is not a transient one but, rather, an indicator of a long-term trend—a response to the continuing shift in the industrialized countries toward less materials-intensive economies.[64]

Given this long-term prospect of saturated markets for many basic products in the industrial countries, shifting the mix of production to exploit mass markets *within* developing countries is a more promising way to realize sustained long-term economic growth and, thus, is in the *long-term* self-interest of the elite. Of course, no country can have mass markets for manufactured goods if its people don't have income—hence, the necessity of meeting the basic human needs of the poor, of generating gainful employment, and of improving the productivity of the agricultural sector, in which so many of the poor labor.

A major challenge for the enlightened elite is to induce their fellow elite to reinvest their capital at home instead of in the industrialized countries, where it is safe from political overthrow and it might earn more in the short term. But, of course, the flight of capital is a problem whatever energy strategy is chosen.

A major advantage of end-use energy strategies in developing countries is that they could help resolve important social problems strongly linked to energy use. The reduced requirements for imported oil and the net reduction in capital requirements for the energy system would mean smaller expenditures of foreign exchange for such purposes, making it easier for the indebted developing countries to service their debts. Emphasis on efficient use of biomass would also help reduce deforestation, desertification, and soil erosion. Modernization of bioenergy would not only help reduce oil imports and increase self-reliance but would also generate employment and stimulate domestic technological development.

International Actions

If implemented, the national energy policies discussed here would go a long way toward making ours a more equitable, more environmentally sound, more self-reliant, and more peaceful world. But providing support for national programs in developing countries that help those countries become more self-reliant or dealing with international or global problems may require international cooperation.

Helping Developing Countries Become More Self-Reliant. Most developing countries have been forced to depend on international aid for their energy activities because they lack capital, technical resources, and adequate energy infrastructures. The energy expenditures of the multilateral and bilateral aid agencies totaled about $14 million between 1972 and 1980. *(See Table 24.)* The bulk of this expenditure came from the large development banks, but bilateral aid accounted for about 30 percent of the total.

Energy supply has dominated all energy aid programs. More than 90 percent of the expenditures have gone into large systems for generating, transmitting, and distributing electricity (mainly hydroelectric power). Fossil fuel exploration has accounted for about 5 percent and new and renewable energy sources for about 3 percent. Efforts on the demand side, directed mainly at industrial conservation, have accounted for less than 1 percent of the total.

It remains unclear how much energy-related aid is needed to implement end-use energy strategies in developing countries. "Front-end" costs of many of the technologies (improved cooking stoves, biogas plants, producer gas generators and engines, biomass-fired gas turbine cogeneration systems, more efficient light bulbs, variable-speed drives for motors, etc.) are relatively modest.

The challenge of implementing end-use energy strategies is not so much in the amount of capital required as in the institutional hurdles. Once a decision has been made to build a $2 billion nuclear power plant, con-

Table 24. Expenditures of Multilateral and Bilateral Aid Agencies in the Energy Area (millions of current dollars)

	Conventional Power Generation (Hydro, Nuclear, Thermal), Transmission, Distribution; Power Sector Studies	**Fossil Fuels Recovery (includes Studies and Training)**	**New and Renewables (includes Geothermal, Fuelwood)**	**Technical Assistance, Energy Planning, Other**	**Total Energy Aid**
MULTILATERAL AID					
World Bank (FY 1972–December 1978)	5,210	305	170	—	5,686
Inter-American Development Bank (FY 1972–FY 1978)	2,596	158	4	—	2,758
Asian Development Bank (FY 1972-FY 1978)	1,183	21	0	—	1,204
European Development Fund (to May 1978)	141	—	9	—	150
U.N. Development Programme (to Jan. 1979)	72	23	29	13	137
U.N. Center for Natural Resources, Energy and Transport (to Jan. 1979)	3	5	4	5	17
Subtotal	9,205	512	216	18	9,952

struction is relatively straightforward, and it is achievable by a fairly small, disciplined team. On the other hand, the number of people involved in spending $2 billion on end-use technologies—say, on the construction and distribution of efficient cooking stoves—is likely to be large and the task far more complicated.

If the international aid community is committed to helping developing countries implement end-use energy strategies, aid programs must be restructured. To begin, the aid agencies and development banks will have to give less project and more program support. Typically, big energy supply efforts, such as the construction

Table 24. Continued

	Conventional Power Generation (Hydro, Nuclear, Thermal), Transmission, Distribution; Power Sector Studies	Fossil Fuels Recovery (includes Studies and Training)	New and Renewables (includes Geothermal, Fuelwood)	Technical Assistance, Energy Planning, Other	Total Energy Aid
BILATERAL AID					
French Aid (1976–1979)	229	16	30	5	280
Canadian International Development Agency (1978–1979, 1979–1980)	88	0	2	1	91
German Aid (1970–present)	1,925	41	81	48	2,095
Kuwait Fund (FY 1973–FY 1978)	437	99	1	—	536
Netherlands—Dutch Development Cooperation (1970–present)	119	71	7	2	198
U.K. Overseas Devel. Admin. (1973–present)	146	1	3	—	149
U.S. AID (FY 1978–FY 1980)	403	2	96	46	546
Grand Total	12,719	757	437	121	14,033
Percentage in Each Sector	91	5	3	1	100

Source: T. Hoffman and B. Johnson, *The World Energy Triangle* (Cambridge, Massachusetts: Ballinger, 1981).

of hydroelectric facilities, lend themselves to a project-oriented approach. But end-use energy strategies require broad program support because they involve diverse and often small-scale technologies tailored to regional and local conditions.

One objection often raised about such a shift is that many developing countries lack the technological and management institutions and expertise to plan and administer such programs. In fact, one reason aid flows to projects instead of programs is that aid agencies that support projects need not rely much on local institutions and capabilities.

The only way to overcome this weakness is to build institutions and strengthen indigenous capabilities. Admittedly, this task is time-consuming and often frustrating, but the long-term payoffs would be well worth the effort. By helping developing countries implement end-use energy strategies, aid agencies would make it easier for them to discharge their debts; continuing to emphasize increasingly unaffordable energy supply projects would have the opposite effect. Accordingly, aid agencies would do well to resist the temptation to achieve quick successes with big projects that undermine self-reliance.

Aid agencies should direct a portion of these expenditures to energy institution-building in developing countries or to modernizing existing institutions, such as the large utility companies. A possible model is the Rockefeller Foundation's 20th-Century contributions to building medical institutions.

Further, indigenous energy-related technical capabilities should be strengthened. Typically, aid has not effectively fostered indigenous technical capability, partly because large projects require highly specialized support services. As a result, project procurement and consulting arrangements in developing countries are frequently left to foreign countries, which become better and better at providing these services. Perhaps more important, most large loans and grants managed by international or bilateral organizations are made specifically to cover expenses requiring foreign currency. Local expenditures are rarely covered by the loans. Because a typical loan covers about one-third the overall project cost, most aid money therefore is spent on consulting and engineering services and on imported machinery. These practices, which recycle the aid back to the donor country, do not encourage self-reliant development. Instead indigenous technical capability would be strengthened if it is stipulated that: (1) foreign consultants cannot be recruited unless it is shown that they are essential, (2) when foreign consultants are hired, measures be taken to associate local groups with the programs, and (3) a significant fraction of the aid must be spent in the recipient country so that it helps build local technical capability.

Such changes will be difficult to sell politically in the donor countries, where support for "foreign aid" often hinges on the purchase of products and services from the donor country. But a technically self-reliant developing country will be better able to buy the high-technology exports of industrialized countries, such as computers, lasers, fiber optics, pharmaceuticals, and biotechnology products.

Finally, some aid should be used to support first-of-a-kind commercial demonstrations to promote technological leapfrogging in rapidly industrializing developing countries instead of technological hand-me-downs from industrialized countries.

Coping with Global Problems. Global insecurity owing to overdependence on Middle East oil, the prospect of global climate change associated with excessive use of fossil fuels, and the risk of nuclear weapons proliferation associated with large-scale use of nuclear power—all are global problems, the resolution of which may require collective global actions.

BRINGING STABILITY TO THE WORLD OIL MARKET We argue here for oil taxes or tariffs that would stabilize consumer oil prices, thus stimulating investments in improved energy efficiency. However, a country might be concerned that its taxes or tariffs would make its industries less competitive in world markets.

This problem could be overcome if oil-importing countries cooperatively levied tariffs or taxes on oil. A cooperative effort would inhibit such shifts in industrial market share among the participating countries, and each would benefit from the lower world oil prices resulting from the oil-saving efforts of others.

Even oil exporters would benefit in the long run from such a cooperative effort because the resulting stable consumer oil prices would reduce uncertainties about the future demand for oil, thus making planning for investments in new oil production capacity less risky.

As in the case of a national tax or tariff, there are many questions about how and at what levels cooperative taxes or tariffs should be administered. Achieving such an agreement would be a heroic political accomplishment, but the mutual benefits of achieving some kind of agreement would be enormous. How much longer can the world economy endure the roller-coaster trend in the world oil price? *(See Figure 1.)*

The challenge of implementing end-use energy strategies is not so much in the amount of capital required as in the institutional hurdles.

LIMITING THE ATMOSPHERIC CARBON DIOXIDE LEVEL The gradual phasing out of coal use proposed here to manage the carbon dioxide problem over the next several decades is perhaps the most formidable political challenge of an end-use energy strategy. Some kind of CO_2 control treaty, limiting coal use through taxes or other mechanisms, may be needed. Such a treaty might involve just three countries—the United States, the USSR, and China—which together account for nearly 90 percent of the world's estimated coal resources.

Limiting CO_2 emissions would be far more politically difficult than cooperatively administering an oil tariff or tax because the benefits to individual countries are less clear. In a global warming, some countries would be worse off, but others might be better off. To complicate matters, it cannot yet be ascertained who the winners and losers would be.

With emphasis on efficient end-use technology, however, a CO_2 control treaty may not be necessary. Coal is cheap, but using it is not. Coal is a dirty fuel, requiring much more capital investment than either oil or natural gas to use in environmentally acceptable ways. In an energy-efficient future, with global energy demand growing hardly at all, coal would be a much less desirable fuel than it would be if energy demand were growing rapidly.

Pursuit for energy efficiency is probably the best single strategy for coping with the CO_2 problem over the next several decades. So doing would both limit the CO_2 build-up in this period and buy time for developing alternative energy sources, such as hydrogen based on the use of amorphous silicon solar cells.[65]

CONTROLLING NUCLEAR WEAPONS PROLIFERATION The main institutional deterrent today to the "horizontal proliferation" of nuclear weapons is the Non-Proliferation Treaty (NPT). Despite its merits, the NPT has failed to attract several countries as signatories, and it does not forbid the nuclear fuel-reprocessing and plutonium-recycling activities that could bring nations dangerously close to nuclear weapons capability.

The countries most closely allied to the United States and the Soviet Union appear to have accepted the two-caste system underlying the NPT, in which the world is formally divided into countries with weapons and those without. But many taking a more independent path—among them, Argentina, Brazil, India, Iran, Israel, Pakistan, South Africa, South Korea, Taiwan, and Yugoslavia—have not formally rejected the nuclear weapons option, and most have failed to ratify the treaty. Most also have both a technology base and experience in nuclear energy, enabling them to build nuclear weapons if they want to, and thus are considered "threshold" countries.

These "threshold" countries are not likely to oppose further proliferation of nuclear weapons or to support far-reaching international controls over nuclear power as long as the current non-proliferation system remains so discriminatory. A country that formally renounces nuclear weapons can be seen as accepting a fundamental restriction on its political independence, condemned to neocolonial status with respect to the superpowers. As a result, under the present ground rules, there seems no prospect of widening support for the NPT.

Even more serious, the groundwork for reprocessing and recycling plutonium in the industrialized countries has already created demand for these technologies in Argentina, Brazil, Pakistan, South Korea, Taiwan, and elsewhere, including several countries that have ratified the NPT.[66] Such a demand is inspired by a combination of technical considerations, desires for prestige, and military motives. Their many-sided character is what makes the plutonium fuel cycle technologies so troublesome: nations can move step-by-step toward a weapons capability without having to decide or announce their ultimate intentions in advance. This "latent proliferation" undermines the effectiveness of present nuclear safeguards.

Latent proliferation is not significantly constrained by the NPT because the treaty permits the development of all types of civilian nuclear power facilities without discrimination. In fact, under Article IV, parties to the treaty agree to facilitate the "fullest possible" exchange of equipment, materials, and information for the peaceful use of nuclear energy. Even countries that have ratified the NPT are moving closer to the technical capability to produce nuclear weapons. Under extraordinary circumstances, they could withdraw from the treaty on relatively short notice.

End-use energy strategies can provide the basis for formulating a more hopeful non-proliferation policy that also makes economic sense—as is indicated by considerations of the proliferation risks and economic aspects of different parts of the nuclear fuel cycle.

As long as plutonium remains in spent fuel, it is protected against diversion to weapons purposes by the intense radiation from the fuel elements. Plutonium can be separated only by reprocessing the spent fuel, and there are no sound reasons for doing so at present.[67] Reprocessing spent fuel to recover the plutonium for recycling in today's reactors is uneconomical, and there is no need to reprocess spent fuel for breeder reactors (which require plutonium as fuel).

Even if nuclear power grows moderately rapidly, the world's nuclear power systems would not be constrained by limited supplies of uranium for at least 50 years.[68] The need for plutonium recycling and breeder reactors would be far less with the nuclear power scenario we have described. *(See Chapter III.)*

Finally, the argument that the disposal of nuclear power wastes requires reprocessing does not stand up to critical analysis. There appear to be no inherent problems with direct spent-fuel disposal, though no satisfactory long-term waste disposal scheme has yet been developed for either spent fuel or reprocessed fuel.[69]

An important policy option for reducing the risk of proliferation would be to avoid reprocessing spent fuel. Imposing such a constraint on non-nuclear weapons countries, whether NPT signatories or not, would be possible only if the nuclear weapons countries engaged in the vertical proliferation of nuclear weaponry accepted parallel obligations—certainly on their civilian power programs but perhaps also on their weapons programs, because the problems of horizontal and vertical proliferation of nuclear weapons are inevitably, intimately, and inextricably linked. A global policy to avoid reprocessing spent fuel from civilian power programs (implemented through an international agreement) might have to be supplemented by a policy (agreed to by the nuclear weapons countries) not to reprocess spent fuel to produce plutonium for weapons. To secure the threshold countries' support for effective non-proliferation conditions, international safeguards should discriminate as little as possible between nuclear and non-nuclear weapons countries. This symmetry of obligations might even be formalized in a new non-proliferation treaty to replace the present NPT.[70]

It is possible to entertain such possibilities for limiting the dangers of proliferation because plutonium recycling technologies are not economic and may never be needed, largely because of progress in and future prospects for the more efficient use of energy.

Conclusion

Precisely what combination of policies is needed to implement end-use energy strategies and how best to carry out these policies cannot be known *a priori.* Different approaches will have to be tried and modified in light of experience. But what is clear is that the required effort probably involves only the coordinated use of familiar policy instruments. The creation of a new world order does not appear to be a precondition for bringing about a global energy future radically different from what is usually projected.

The creation of a new world order does not appear to be a precondition for bringing about a global energy future radically different from what is usually projected.

The energy future we have outlined here is not the ultimate answer to the world's energy problems. Eventually, the world will need economical and environmentally benign renewable energy sources—the development of which will take time and ingenuity. But this future would give our children and grandchildren a world free of draconian energy-production regimes and, we hope, a world sufficiently prosperous and peaceful to allow them to work out long-term solutions to energy problems. It should give them a little breathing space and some room to maneuver.

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Appendix

A Top-Down Representation of Our Bottom-Up Global Energy Demand Scenario

The "bottom-up" or end-use construction of the global energy demand scenario presented in Chapter IV and summarized in Figure 9 will be unfamiliar to those more accustomed to "top-down" model representations of the energy future.

To express our global energy demand scenario in terms more familiar to most energy modelers, we have constructed a simple model relating *commercial* final energy demand per capita (FE/P) to gross domestic product per capita (GDP/P), the average price of final energy (P_e), a rate of energy efficiency improvement (c) that is not price-induced, an income elasticity (a), and a long-run final energy price elasticity (-b):

$$FE/P\ (t) = A \times [GDP/P\ (t)]^a \times [P_e\ (t)]^{-b} / (1 + c)t,$$

where "A" is a constant. This is the aggregate energy demand equation underlying the Institute for Energy Analysis/Oak Ridge Associated Universities (IEA/ORAU) global energy-economy model.[1] Here the equation is applied separately to industrialized and developing countries, relating FE/P, GDP/P, and P_e values in 2020 to those in 1972 for illustrative values of the parameters (a, b, and c).

Figures A1 and A2 show per capita GDP and energy-price parameters consistent with this study's energy demand scenarios for industrialized countries and for developing countries, respectively, for alternative assumptions about income and price elasticities and the non-price-induced energy-efficiency improvement rate.

The year 1972 is chosen as the base year for this modeling exercise because it is the last year before the first oil price shock, so presumably the economic system was then in equilibrium with the existing energy prices (unlike the situation in 1980, say). For this base year, the values of FE/P were 4.7 kW and 0.38 kW, compared to the 2020 scenario values of 2.5 kW and 1.0 kW for industrialized and developing countries, respectively. (Note: the commercial energy use values needed for this analysis account for only about half the total final energy use in developing countries at present.)

For the income elasticity a value of 0.8 was selected to capture the effects of the ongoing shift to less energy-intensive economic activity in industrialized countries. The value of unity assumed in many modeling efforts is included for comparison.

For developing countries, income elasticities of 1.4 and 1.1 are assumed for these displays. The value of 1.4 was used for developing countries in the 1983 IEA/ORAU study[2] and may be roughly characteristic of the historical situation in developing countries. However, as developing countries modernize in the decades ahead, the income elasticity can be expected to decline. The two assumed values may span the range of uncertainty for the income elasticity in developing countries for the period of interest here.

As for the long-run price elasticity, Nordhaus has reviewed various studies and has concluded that the range of plausible values is from -0.66 to -1.15,[3] with -0.8 a "best-guess" value based on a judgmental weighting of values from various studies.[4] (These elasticities appear high but they are not. Long-run price elasticities are much larger than short-run elasticities. Likewise, final demand elasticities are greater than secondary demand elasticities, which in turn are greater than primary demand elasticities.[5]) The illustrative values chosen here (-0.7 and -1.0) span most of this range.

The assumed non-price induced energy-efficiency improvement rates are 1.0 and 0.5 percent per year. The higher value is the one assumed for the "CO_2-benign" global energy scenarios developed in a 1983 Massachusetts Institute of Technology Energy Laboratory study;[6] the lower value approximately reflects the contribution from such energy-efficiency improvements in a 1984 IEA/ORAU analysis.[7] The higher energy-efficiency improvement rate is coupled with the lower price elasticity and the lower rate with the higher price elasticity to reflect the tendency of non-price-induced energy-efficiency improvement policies to diminish the efficacy of prices in curbing energy demand.[8]

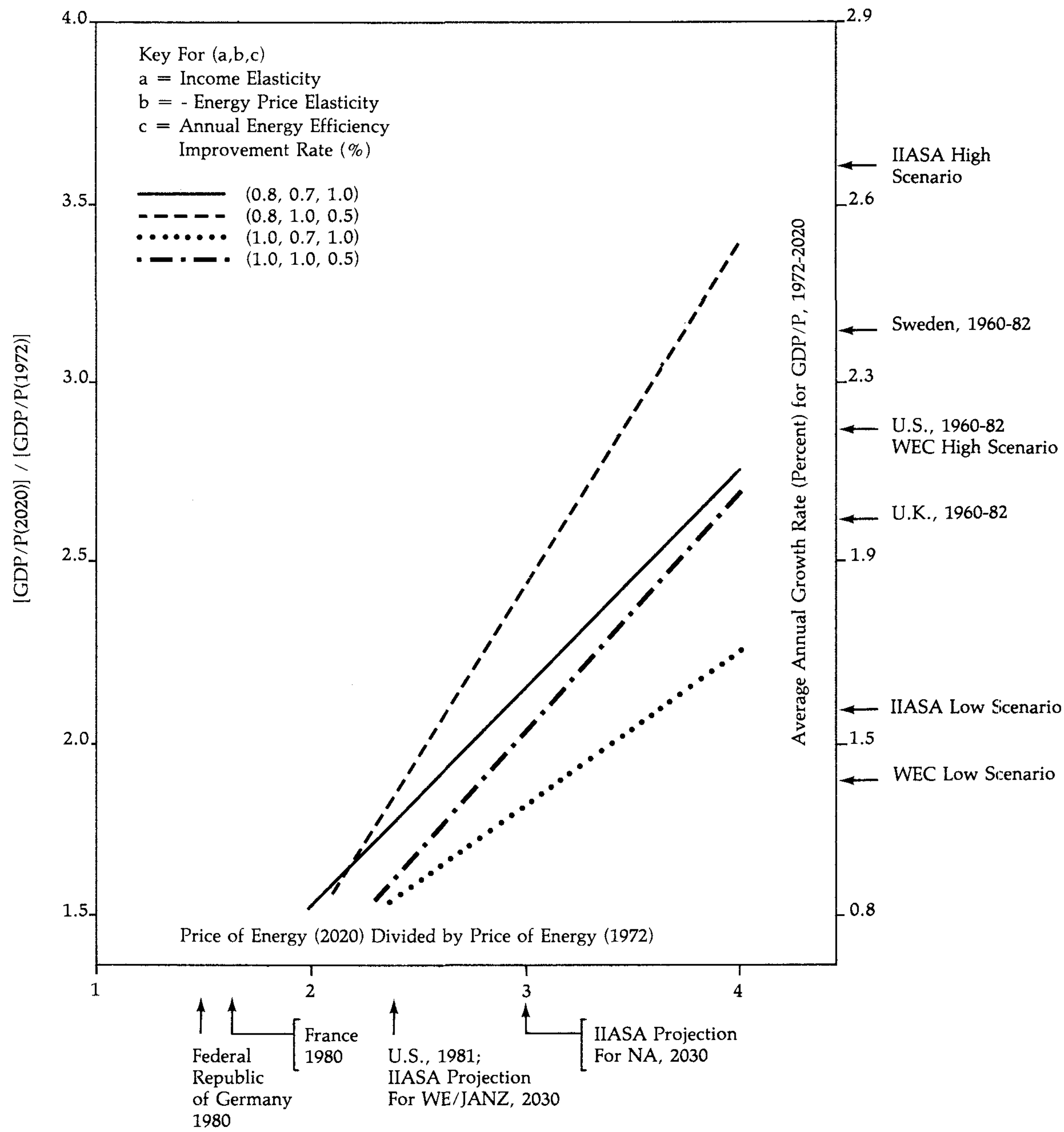
Although we did not make explicit assumptions about energy prices in the construction of our global energy demand scenario (most end-use technologies underlying our analysis would be economic at or near present prices on a life-cycle cost basis, with future costs discounted at market interest rates), there may well be continuing final energy price increases to reflect rising marginal production costs, the expected continuing shift to electricity, and the levy of some energy taxes to take externalities into account. Prices have already risen substantially above 1972 values: in West Germany and France, average final energy prices in 1980 were 1.5 and 1.6 times the 1972 values in real terms, respectively,[9] and in the United States, the average price in 1981 was 2.3 times the 1972 price.[10] Looking to the future, the IIASA study[11] projects that by 2030, final energy prices will be 3 times the 1972 value in all regions except the WE/JANZ region (Western Europe, Japan, Australia, and New Zealand), for which a 2.4-fold increase is projected instead. A 1983 projection by the U.S. Department of Energy is for much larger (3.6-fold to 5.7-fold) average final energy price increases for the United States between 1972 and 2010, associated with an 11- to 17-percent reduction in final energy use per capita in this period.[12] It is reasonable to associate an average increase in the energy price by 2020 somewhere in the range 2 to 3 times the 1972 value with the global energy demand scenario.

For industrialized countries and the cases (a, b, c) = (0.8, 0.7, 1.0) and (0.8, 1.0, 0.5), our energy demand projection is consistent with a 50- to 100-percent increase in per capita GDP (comparable to the values assumed in the IIASA and WEC low scenarios) and 2020 energy prices 2 to 3 times the 1972 values. *(See Figure A1.)* If there were no ongoing structural shift (a = 1.0) to less energy-intensive economic activities, somewhat higher energy prices would be required.

For developing countries, our scenario with 2020 prices in the range of 2 to 3 times 1972 prices and the high-income elasticity (a = 1.4) would be compatible with the per capita GDP growth rates assumed in the IIASA and WEC high scenarios. With the lower-income elasticity (a = 1.1), the base case projection would be consistent with much more rapid GDP growth. *(See Figure A2.)*

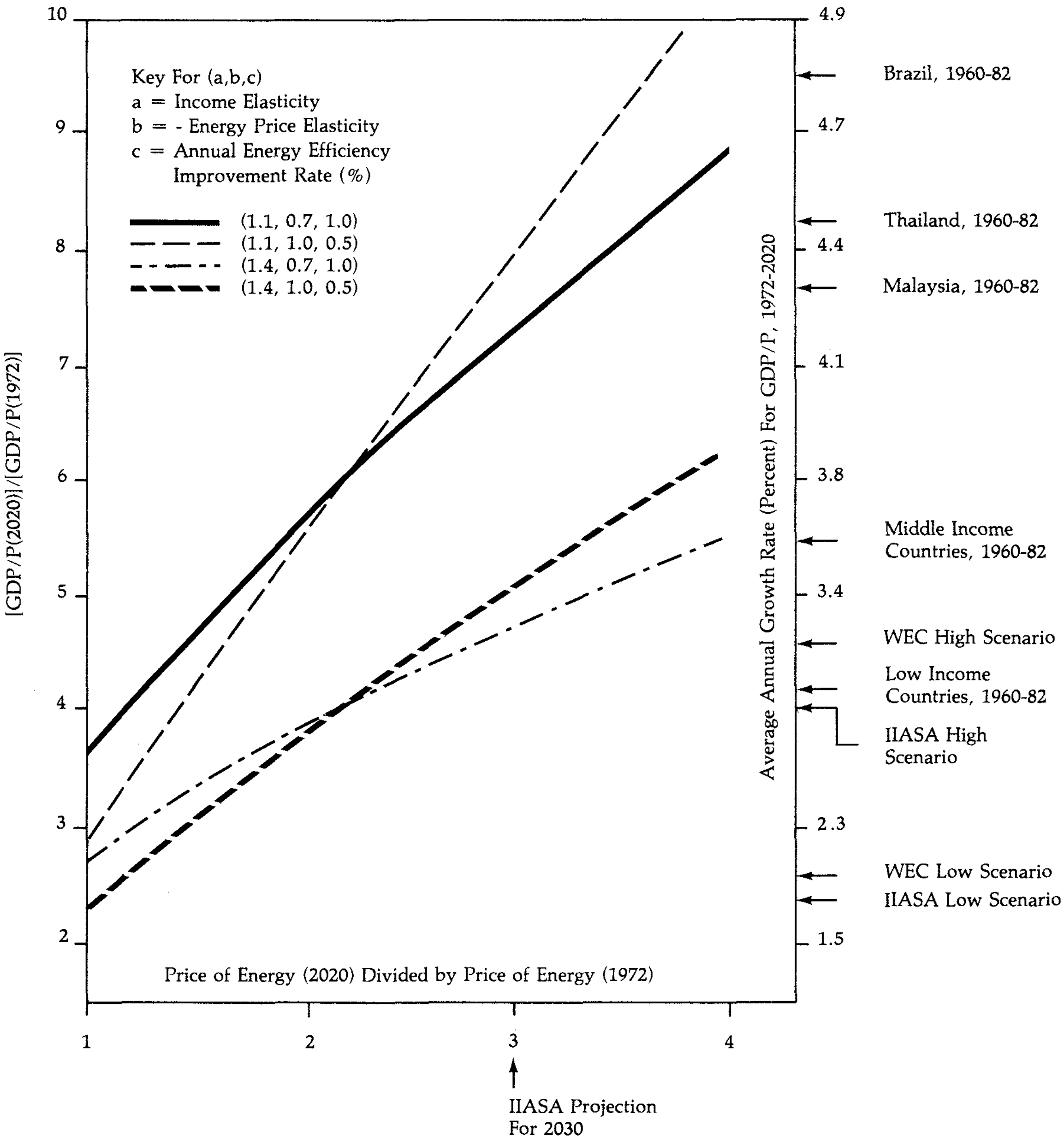
This modeling exercise shows that although our global energy demand projection for 2020 is far outside the range of most other projections, it appears to be consistent with plausible values of income and price elasticities and with

Figure A-1 A Top-Down Representation of Our End-Use Energy Demand Scenario for Industrialized Countries



Each line represents the combinations of per capita gross domestic product and energy price in the year 2020 (relative to 1972 values) consistent with the energy demand scenario developed in Chapter 4 for industrialized countries, for the indicated values of income elasticities, price elasticities, and the nonprice-induced energy efficiency improvement rate.

Figure A-2. A Top-Down Representation of Our End-Use Energy Demand Scenario for Developing Countries



Each line represents the combinations of per capita gross domestic product and energy price in the year 2020 (relative to 1972 values) consistent with the energy demand scenario developed in Chapter 4 for developing countries, for the indicated values of income elasticities, price elasticities, and the nonprice-induced energy efficiency improvement rate.

plausible expectations about energy price and GDP growth, if the non-price-induced energy-efficiency improvement rate can be in the range 0.5 to 1.0 percent per year.

Although the non-price-induced energy-efficiency improvement rate is a measure of the public policy effort that would be required to bring about the energy future described in this study, not all this efficiency improvement would have to be public-policy-induced. Energy-efficiency improvements associated with general technological innovations have often been made even when energy prices have been declining,[13] a phenomenon that led IEA/ORAU analysts to include the non-price-induced technological improvement factor in their model for the industrial sector in the first place.[14]

At the same time, however, the energy-efficiency improvement factor may not represent the full extent of the needed public policy effort if low energy-demand levels were to cause energy prices to stabilize or even fall. In such a case, energy taxes may also be needed to keep gradual upward pressure on final (consumer) prices.

Notes for Appendix

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>
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