Energy: The Solar Prospect
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Dawn of an Era

About one-fifth of all energy used around the world now comes from solar resources: wind power, water power, biomass, and direct sunlight. By the year 2000, such renewable energy sources could provide 40 percent of the global energy budget; by 2025, humanity could obtain 75 percent of its energy from solar resources. Such a transition would not be cheap or easy, but its benefits would far outweigh the costs and difficulties. The proposed timetable would require an unprecedented worldwide commitment of resources and talent, but the consequences of failure are similarly unprecedented. Every essential feature of the proposed solar transition has already proven technically viable; if the 50-year timetable is not met, the roadblocks will have been political—not technical.[1]

Different solar sources will see their fullest development in different regions. Wind power potential is greatest in the temperate zones while biomass flourishes in the tropics. Direct sunlight is most intense in the cloudless desert, while water power depends upon mountain rains. However, most countries have some potential to harness all these renewable resources, and many lands have begun to explore the feasibility of doing so.[2]

A major energy transition of some kind is inevitable. For rich lands and poor alike, the energy patterns of the past are not prologue to the future. The oil-based societies of the industrial world cannot be sustained and cannot be replicated; their spindly foundations, anchored in the shifting sands of the Middle East, have begun to erode. Until recently most poor countries eagerly looked forward to entry into the oil era with its airplanes, diesel tractors, and ubiquitous automobiles. However, the fivefold increase in oil prices since 1973 virtually guarantees that the Third World will never derive most of its energy from petroleum. Both worlds thus face an awesome discontinuity in the production and use of energy.

In the past, such energy transformations invariably produced far-reaching social change. The 18th-century substitution of coal for wood and wind in Europe, for example, accelerated and refashioned the industrial revolution. Later, the shift to petroleum altered the nature of travel, shrinking the planet and reshaping its cities. The coming energy transition can be counted upon to fundamentally alter tomorrow's world. Moreover, the quantity of energy available may, in the long run, prove much less important than where and how this energy is obtained.

Since many energy sources besides the sun could replace oil and gas, we need to know now what consequences the choices we make today will have in 50 years. While we can obviously possess no detailed information about the state of the world 50 years from now, even rough calculations may yield insights of importance for energy policy. If we optimistically assume that the world's population will level off after one more doubling and stabilize at eight billion by 2025, and if we conservatively assume that per capita energy use will then amount to one-third the current U.S. level, we can broadly assess different ways of trying to meet this aggregate demand.[3]

If this energy were all provided by coal, an absolutely intractable problem would result. Coal combustion necessarily produces carbon dioxide and adding CO_2 to the air raises the earth's temperature by retarding the radiation of heat into space (a phenomenon known as the greenhouse effect). Since CO_2 remains in the atmosphere for hundreds or perhaps thousands of years, the impact of CO_2 emissions is cumulative and irreversible on any relevant time scale. At our projected level of coal consumption, the atmospheric inventory of CO_2 would increase about 4 percent a year; such growth in atmospheric carbon dioxide would, virtually all meteorologists agree, soon alter the heat balance of the entire planet dramatically.

If the postulated energy demand were met with nuclear fission, about 15,000 reactors as large as the biggest yet built would have to be constructed—one new reactor a day for 50 years. Sustaining these reactors would require the recycling of 20 million kilograms of plutonium annually. Every year, enough plutonium would be recycled around the world to fabricate four million Hiroshima-size bombs. Such a prospect cannot sanely be greeted with equanimity.

Nuclear fusion is a speculative technology. No one knows what it will cost, how it will work, or even whether it will work. The deuterium-tritium reaction—the "simplest" fusion reaction and the focus of almost all current research—will produce large amounts of radioactive waste and can be used to breed plutonium. Some advanced fusion cycles—most notably those that would fuse two deuterium nuclei or that would fuse a proton with a boron atom—could, theoretically, provide a nearly inexhaustible supply of relatively clean power. But such reactions will be vastly more difficult to achieve than the deuterium-tritium reaction. In short, there is no chance that most of the world's energy demand will be met by fusion in 2025.[4]

Thus we are left with the solar options: wind, falling water, biomass, and direct sunlight. Fortunately, they are rather attractive. Solar sources add no new heat to the global environment, and—when in equilibrium—they make no net contribution to atmospheric carbon dioxide. Solar technologies fit well into a political system that emphasizes decentralization, pluralism, and local control.

Sunlight is abundant, dependable, and free. With some minor fluctuations, the sun has been bestowing its bounty on the earth for more than four billion years, and it is expected to continue to do so for several billion more. The sun's inconstancy is regional and seasonal, not arbitrary or political, and it can therefore be anticipated and planned for.[5]

Our ancestors captured the sun's energy indirectly by gathering wild vegetation. Their harvest became more reliable with the revolutionary shift to planned cultivation and the domestication of animals. As civilization developed, reliance upon the sun grew increasingly circuitous. Slaves and draft animals provided a roundabout means of harnessing large quantities of photosynthetic energy. Breezes and currents—both solar-powered phenomena—drove mills and invited overseas travel.

In earlier eras, people were intensely aware of the sun as a force in their lives. They constructed buildings to take advantage of prevailing winds and of the angles at which the sun's rays hit the earth. They built industries near streams to make power-generation and transport easier. Their lives revolved around the agricultural seasons. In the 14th century, coal began to contribute an increasing fraction of Europe's energy budget—a trend that accelerated greatly in the 18th and 19th centuries. During the past 75 years, oil and natural gas became the principal energy sources in the industrialized world. In the fossil fuel era, the sun has been largely ignored. No nation includes the sun in its official energy budget, even though all other energy sources would be reduced to comparative insignificance if it were. We think we heat our homes with fossil fuels, forgetting that without the sun those homes would be -240° C when we turned on our furnaces. We think we get our light from electricity, forgetting that without the sun the skies would be permanently black.[6]

About 1.5 quadrillion megawatt-hours of solar energy arrive at the earth's outer atmosphere each year. This amount is 28,000 times greater than all the commercial energy used by humankind. Roughly 35 percent of this energy is reflected back into space; another 18 percent is absorbed by the atmosphere and drives the winds; and about 47 percent reaches the earth. No country uses as much energy as is contained in the sunlight that strikes just its buildings. Indeed, the sunshine that falls each year on U.S. roads alone contains twice as much energy as does the fossil fuel used annually by the entire world. The wind power available at prime sites could produce several times more electricity than is currently generated from all sources. Only a fraction of the world's hydropower capacity has been tapped. As much energy could be obtained from biomass each year as fossil fuels currently provide.

How easily and cheaply these vast energy sources can be harvested is disputed. Opinions naturally rest heavily upon the questions asked and the assumptions made. How much distance can separate an ener-

"No country uses as much energy as is contained in the sunlight that strikes just its buildings."

gy facility and its potential users? Will people and industries migrate to take advantage of new energy sources? Should only huge, utility-scale sites be considered or should individual and community-sized sites be counted as well? What limits will environmental, political, and aesthetic factors impose?

Past efforts to tap the solar flow have been thwarted by unreasonable economic biases. The environmental costs of conventional fuels, for example, have until recently been largely ignored. If reclamation were required of strip mining companies, if power plants were required to stifle their noxious fumes, if oil tankers were prohibited from fouling the oceans with their toxic discharges, if nuclear advocates were forced to find a safe way to dispose of long-lived radioactive wastes, conventional power sources would cost more and solar equipment would be more economically competitive. As such costs have been increasingly "internalized," conventional sources have grown more expensive and solar alternatives have consequently become more credible.[7]

Moreover, fuel prices long reflected only the costs of discovery, extraction, refining, and delivery; they failed to include the value of the fuel itself. Over the years, improvements in exploitation techniques drove fuel prices relentlessly downward, but these low prices were chimerical. Although, for example, U.S. oil prices (corrected for inflation) fell 37 percent in the 25 years between 1948 and 1972, the nation was living off its energy capital during this period—not its interest. The world has only a limited stock of fuel, and it was only a matter of time before that fuel began to run out.[8]

Unlike finite fuels, sunlight is a flow and not a stock. Once a gallon of oil is burned, it is gone forever; but the sun will cast its rays earthward a billion years from now, whether sunshine is harnessed today for human needs or not. Technical improvements in the use of sunlight could lower prices permanently; similar technical improvements in the use of finite fuels could hasten their exhaustion.

The current world economy was built upon the assumption that its limited resources could be expanded indefinitely. No nation charged

OPEC-style severance royalties when oil was removed from the earth; depletion allowances were granted to those who exploited it. No nation charged a reasonable "scarcity rent" for fuel; the needs of future generations were discounted to near zero. Now that the world's remaining supply of easily obtainable high-grade fuel is mostly in the hands of single-resource nations with legitimate worries about their long-range futures, prices have increased fivefold in five years. As a consequence, solar energy is rapidly shaking off the false economic constraints that previously hindered its commercial development. In 1976, the United States produced one million square feet of solar collectors; in 1977, the figure is expected to triple.[9]

Since sunlight is ubiquitous and can be used in decentralized facilities, many proposed solar options would dispense with the expensive transportation and distribution networks that encumber conventional energy systems.[10] The savings thus obtained can be substantial; transmission and distribution today account for about 70 percent of the cost of providing electricity to the average U.S. residence.[11] In addition, line losses during electrical transmission may amount to several percent of all the energy produced, and the unsightly transmission tendrils that link centralized energy sources to their users are vulnerable to both natural disasters and human sabotage.

Probably the most important element in a successful solar strategy is the thermodynamic matching of appropriate energy sources with compatible uses. The quality of energy sought from the sun and the costs of collecting, converting, and storing that energy usually correlate directly: the higher the desired quality, the higher the cost. Sources and uses must therefore be carefully matched, so that expensive, high quality energy is not wasted on jobs that do not require it.[12]

No country has undertaken a comprehensive inventory of the quality of energy it uses throughout its economy. Moreover, the energy currently employed for various tasks is often of far higher quality than necessary. The use of nuclear reactors operating at a million degrees C to make electricity to run residential water heaters to provide bath water at 30° C is surely the height of thermodynamic foolishness.

Preliminary calculations suggest that roughly 34 percent of end-use energy in the United States is employed as heat at temperatures under 100° C; much of this energy heats buildings and provides hot water. Another 24 percent is for heat at temperatures of 100° C or higher, much of it for industrial processes. Thirty percent of end-use energy is employed to power the transportation system; 8 percent is used as electricity and 3 percent as miscellaneous mechanical work. In Canada, a somewhat higher percentage is used for low-grade heat and somewhat less is used for transportation. Although both countries are highly industrialized, highly mobile, and have high energy use-GNP ratios, most of the energy budgets of both could easily and economically be met using existing solar technologies.[13]

Cheap, unsophisticated collectors can easily provide temperatures up to 100° C. Selective surfaces—thin, space-age coatings that absorb much sunlight but re-radiate negligible heat—greatly increase the temperatures that collectors can attain. Because air conducts and convects heat, high-temperature collectors are often sealed vacuums. Focusing collectors, which use lenses or mirrors to focus sunlight into a small target area, can obtain still higher temperatures. The French solar furnace at Odeillo, for instance, can reach temperatures of about 3000° C.

Solar thermal-electric plants appear economically sound, especially when operated only to meet daytime peak demands or when crossbred with existing plants that use other fuels for night-time power production. Ocean thermal facilities may be a source of base-load electricity in some coastal areas. Decentralized photovoltaic cells will be the most attractive source of solar electricity if the cost reductions commonly projected materialize.

Wind power can be harnessed directly to generate electricity. But because electricity is difficult to store, some wind turbines might best be used to pump water into reservoirs or to compress air. The air and water can then be released as needed to generate electricity or to perform mechanical work. Energy from intermittent sources like wind machines can also be stored as high temperature heat or in chemical fuels, flywheels, or electrical batteries.

Biological energy sources, which include both organic wastes and fuel crops, could by themselves yield much of the world's current energy needs. Such sources can provide liquid and gaseous fuels as well as direct heat and electricity. Particularly attractive in a solar economy would be the use of biomass for the co-generation of electricity and industrial process steam.

While no single solar technology can meet humankind's total demand for energy, a combination of solar sources can. The transition to a solar era can be begun today; it would be technically feasible, economically sound, and environmentally attractive. Moreover, the most intriguing aspect of a solar transition might lie in its social and political ramifications.[14]

Most policy analyses do not encompass these social consequences of energy choices. Most energy decisions are based instead on the naive assumption that competing sources are neutral and interchangeable. As defined by most energy experts, the task at hand is simply to obtain enough energy to meet the projected demands at as low a cost as possible. Choices generally swing on small differences in the marginal costs of competing potential sources.

But energy sources are *not* neutral and interchangeable. Some energy sources are necessarily centralized; others are necessarily dispersed. Some are exceedingly vulnerable; others are nearly impossible to disrupt. Some will produce many new jobs; others will reduce the number of people employed. Some will tend to diminish the gap between rich and poor; others will accentuate it. Some inherently dangerous sources can be permitted widespread growth only under authoritarian regimes; others can lead to nothing more dangerous than a leaky roof. Some sources can be comprehended only by the world's most elite technicians; others can be assembled in remote villages using local labor and indigenous materials. Over time, such considerations may prove weightier than the financial criteria that dominate and limit current energy thinking.

Appropriate energy sources are necessary, though not sufficient, for the realization of important social and political goals. Inappropriate

"Most energy decisions are based on the naive assumption that competing sources are neutral and interchangeable."

energy sources could make attaining such goals impossible. Decisions made today about energy sources will, more than most people imagine, determine how the world will look a few decades hence. While energy policy has been dominated by the thinking of economists and scientists, the crucial decisions will be political.

The kind of world that could develop around energy sources that are efficient, renewable, decentralized, simple, and safe cannot be fully visualized from our present vantage point. Indeed, one of the most attractive promises of such sources is a far greater flexibility in social design than is afforded by their alternatives. Although energy sources may not dictate the shape of society, they do limit its range of possibilities; and dispersed solar sources are more compatible than centralized technologies with social equity, freedom, and cultural pluralism. All in all, solar resources could power a rather attractive world.

Solar Heating and Cooling

Solar energy is most easily captured as low-grade heat. Development of the flat-plate collector that is used to catch such heat is generally credited to the 18th century Swiss scientist Nicholas de Saussure, who obtained temperatures over 87° C using a simple wooden box with a black bottom and a glass top. The principle used by de Saussure is simple: glass is transparent to sunlight but not to the radiation of longer wavelengths given off by the hot collector itself. Sunlight flows easily through the glass top into the collector where it is trapped as heat. The modern flat-plate collector operates on this same basic principle, although improved materials achieve much higher temperatures and are more durable. Simple and easy-to-make solar collectors could supply heat now provided by high-quality fuels. More than one-third of the energy budget of all nations is spent to produce heat at temperatures that flat-plate solar collectors can achieve.[15]

The simplest task to accomplish directly with solar power is heating water, and solar water heaters are being utilized in many countries. More than two million have been sold in Japan, and tens of thousands are in use in Israel. In the remote reaches of northern Australia, where fuels are expensive, solar water heaters are required by law on all new buildings. Until replaced by cheap natural gas, solar water heaters were much used in California and in Florida; Miami alone had about 50,000 in the early 1950s. Since 1973, interest in solar water heaters has rekindled in many parts of the world. In poorer countries, cheap hot water can make a significant contribution to public well-being: hot water for dishwashing and bathing can reduce the burden of infectious diseases, and clothes washed with hot water and soap outlast clothes beaten clean on rocks at a river's edge.

Sunlight can also be used to heat buildings. All buildings receive and trap radiant energy from the sun. Warming a home on a winter day, this heat may be desirable; but it can constitute indecent exposure, broiling and embroiling the occupants of an all-glass office building in mid-summer. Solar buildings, designed to anticipate the amount of solar energy available in each season, put sunlight to work. To harness diffuse solar energy to meet a building's needs, options that vary in efficiency, elegance, and expense can be employed.[16]

Solar heating systems for buildings can be either "active" or "passive." In active systems, fans and pumps move air or liquid from a collector first to a storage area and then to where it is needed. Passive systems store energy right where sunlight impinges on the building's structural mass; such systems are designed to shield the structure from unwanted summer heat while capturing and retaining the sun's warmth during the colder months. Passive solar buildings act as "thermal flywheels," smoothing the effects of outside temperature fluctuations between day and night—a principle as old as the ancient thick-walled structures of Mohenjo-Daro in the Indus Valley and the adobe Indian pueblos in the American Southwest. Although more money and attention has been lavished upon active systems, many of the world's most successful solar buildings employ simple, inexpensive passive designs.

In the latitudes that girdle the Earth between 35° N and 35° S, roofs of buildings can be built to serve as passive solar storage devices. For this region, American designer Harold Hay has built a "skytherm" house, the flat roof of which is covered by large polyethylene bags filled with water. By adroitly manipulating slabs of insulation over the roof during the day or night, Hay can heat the house in the winter and cool it in the summer. A.K.N. Reddy and K.K. Prasad at the Indian Institute of Science in Bangalore have suggested a similar, but less expensive design for poor countries; their model uses rooftop ponds of water.

In latitudes above 35° either north or south, a flat roof can catch less and less of the low winter sun. Vertical walls and steep roofs are more effective solar collectors in these regions than are flat roofs. In France, Felix Trombe and Jacques Michel have built several solar houses, each with a glass wall facing south and a thick concrete wall located a short distance inside the glass. Openings near the top and bottom of the concrete walls create a natural circulation pattern as hot air rises and moves into the living areas while cool air flows through the bottom opening into the solar-heated space between the glass and the concrete. During the summer, when additional heat is unwanted, the top air passages are closed and the rising air is channeled outside. This same approach has been successfully employed by Doug Kelbaugh in his passive solar house in Princeton, New Jersey.

In addition to such passive approaches, hundreds of active solar heating systems have been built, using a variety of collectors and storage systems. Each technology stresses certain features—good performance, rugged durability, attractive appearance, or low cost—each of which is often achieved at the sacrifice of others. The U.S. effort has been by far the most expensive and ambitious, though important work has been done in the Soviet Union, Great Britain, Australia, Japan, Denmark, Egypt, and Israel.

Flat-plate solar collectors suffice for normal heating purposes. After heat has been collected and then transported to storage reservoirs, most active solar heating systems use conventional technologies (water radiators or forced-air ducts) to deliver it to the living areas as needed.

Solar collectors are being used in diverse locations to heat buildings. The town of Mejannes-le-Clap in southern France has announced plans to obtain most of its heat from the sun. Several U.S. solar-heated communities, as well as individual schools, meeting halls, office buildings, and even hamburger stands, are now under construction. Saudi Arabia plans to build a new town at Jubail, using sunlight for heating, for cooling, and for running water pumps; the Saudis are now also building the world's largest solar-heated building —a 325,000 square foot athletic fieldhouse—in Tabuk.

Storing heat for a couple of days is not difficult; heated water or gravel will do the job if a large insulated storage bin is used. Eutectic salts [illegible] that absorb prodigious amounts of heat when they [illegible] release it when they re-solidify, can reduce the minimum storage volume needed by a factor of six. The most serious problems plaguing the storage of heat in phase-changing eutectic salts have been overcome, according to Dr. Maria Telkes, a leading American expert in solar thermal storage.[17]

In the 1940s, the Japanese built an energy storage system that worked on an annual cycle. During cold months, heat was pumped from a large container of water; by the end of the winter, a huge block of ice had formed, into which excess building heat was cast during the summer. The Japanese concept was recently revived by Harry Fischer of the Oak Ridge National Laboratory in Tennessee. Fischer found that when combined with a solar collector, a radiator, and an efficient heat pump, such an annual storage system can perform admirably over a wide range of climates. Fischer's prototype worked so well that several private companies decided to develop the concept further.[18]

Many simple solar technologies can be used to cool buildings. Simple ceiling vents may suffice to expel hot air, at the same time drawing cooler air up from a basement or well. In dry climates, evaporative coolers can be used to chill the air. In more humid areas, solar-absorption air conditioners may be needed. The logical successors to contemporary cooling units, solar air conditioners are currently being developed in Japan and the United States. While early solar air conditioners required heat at about 120° C for optimum performance, a Japanese company has developed a unit that operates satisfactorily

"The day is dawning when heating and cooling self-sufficiency will be an economical option for most new buildings."

at 75° C—a temperature any commercial solar collector can easily muster. Fortuitously, solar air conditioners reach peak cooling capacity when the sun burns brightest, which is when they are most needed. Consequently, solar air conditioners could reduce peak demands on many electrical power grids. As cost-effective solar air conditioners reach the market, the overall economics of solar systems will improve because the collectors will begin providing a year-round benefit.[19]

It is harder in temperate than in tropical regions to provide with solar technologies 100 percent of the heat buildings need. It is generally cheaper at present to get supplementary heat during long cloudy periods from conventional fuels, wind power, biogas, or wood. However, when solar equipment is mass-produced, prices should plummet, while fossil fuel prices can only climb. Moreover, major improvements in the design of collectors, thermal storage systems, and heat-transfer mechanisms are being made. Indeed, the day is dawning when heating and cooling self-sufficiency will be an economical option for most new buildings.

Solar heating systems are most attractive when considered in terms of "lifetime costs"; the initial investment *plus* the lifetime operating costs of solar systems often total less than the combined purchase and operating costs of conventional heating systems. For example, recent U.S. studies have shown solar heating to be more economical than electrical heating except in competition with cheap hydropower.[20]

Investments in solar technologies can be mortgaged at a steady cost over the years, while the fuel costs of alternative systems will rise at least as fast as general inflation. In fact, the initial cost alone of solar heating systems often amounts to less than the initial cost of electrical resistance heating, if the cost of the building's share of a new power plant and the electrical distribution system is included. However, the cost of a solar heating system must be borne entirely by the homeowner, while a utility builds the power plant and strings the power lines. The utility borrows money at a lower interest rate than the homeowner can obtain, and it averages the cost of electricity from the expensive new plant with that of power from cheap plants built decades earlier so that true marginal costs are never compared.[21]

Solar heated buildings are now commercially viable. However, large-scale changes in the housing industry are not accomplished easily—witness the 30,000 autonomous building code jurisdictions in the United States. The building industry is localized—even the giant construction firms each produce fewer than one-half of one percent of all units. Profit margins are small, and salability has traditionally reflected the builder's ability to keep purchase prices low. Nonetheless, a respected market research organization, Frost and Sullivan, predicts that 2.5 million U.S. residences will be solar heated and cooled by 1985, and the American Institute of Architects has urged an even more ambitious solar development program.[22]

Solar heating becomes even more attractive when it is crossbred with other compatible technologies. Its happy marriage to absorption air-conditioners and heat pumps has already been mentioned. Greenhouses too can be splendid solar collectors, producing much more heat than they need in even the dead of winter, if they are tightly constructed, well insulated, and fitted with substantial thermal storage capacity. Whereas many old-style attached greenhouses placed demands on the heating system of the main house, inexpensive solar greenhouses can actually furnish heat to the living area while they extend the growing season for home-grown vegetables. A program to build greenhouses for low-income families in northern New Mexico out of local materials, low-cost fiberglass, and polyethylene has already proven successful.

In addition to warming buildings, low-grade heat from simple solar devices can also be used to dry crops—a task that now often consumes prodigious amounts of propane and methane gas. Solar dryers are now being used to remove moisture from lumber and textiles, as well as from corn, soybeans, alfalfa, raisins, and prunes. The sun has always been used to dry most of the world's laundry.

For more than a century, solar advocates have gathered crowds by cooking food with devices that use mirrors to intensify sunlight.

Now that firewood supplies are growing scarce in many parts of the Third World, solar cooking is being taken more seriously. Although solar cookers proved popular in some village experiments in the 1960s, their high cost, as much as $25 each, prohibited widespread use. Today, however, cheap new reflecting materials like aluminized mylar can be stretched over inexpensive locally-made frames. In poor countries, solar cookers will be only supplementary devices for now, since these mechanisms cannot function at night or in cloudy weather and since storing high-temperature heat is expensive. But if heat storage technology advances, solar stoves and ovens may play an increasingly important role in rich and poor countries alike.

Solar technology now also encompasses desalination devices that evaporate water to separate it from salt. In the late 19th century, a huge solar desalination plant near Salinas, Chile, provided up to 6,000 gallons of fresh water per day for a nitrate mine. Recent research has led to major improvements in the technology of solar desalination, especially to improvements in "multiple-effect" solar stills. Today, this sun-driven process holds great promise, especially in the Middle East and other arid regions. A small Soviet solar desalination plant in the Kyzyl Kum Desert in central Asia now produces four tons of fresh water a day.[23]

Relatively low temperature sources of heat can also be used to operate pumps and engines. In the 1860s, Augustin Mouchot, a French physicist, developed a one-half horsepower solar steam engine. In the early 20th century, more efficient engines were built using ammonia or ether instead of water as the working fluid. In 1912, Frank Shuman constructed a 50-horsepower solar engine near Cairo to pump irrigation water from the Nile.

Scores of solar devices were built around the world in the early decades of this century, but none withstood the economic competition of low-cost fossil fuels. In recent years, with fuel prices soaring, solar pumps have begun to attract attention again. In 1975, a 40-horsepower solar pump of French design was installed in San Luis de la Paz to meet this Mexican town's irrigation and drinking needs. Mexico has ordered ten more such pumps; and Senegal, Niger, and Mauritania have installed similar devices. At present, solar pumps make economic sense only in remote areas where fuel and maintenance costs for conventional systems are extremely high. But, many authorities believe, the costs of solar pumps could be dramatically reduced by taking advantage of the findings of further research and the economies of mass production.[24]

Solar energy can be used directly in various industrial processes. A study of the Australian food-processing industry found, for example, that heat comprised 90 percent of the industry's energy needs; almost all this heat was at under 150° C, and 80 percent was below 100° C. Such low-temperature heat can be easily produced and stored using elementary solar technologies. Similarly, a study of an Australian soft-drink plant found that enough collectors could be retrofitted onto the factory's roof to provide 70 percent of all the plant's heat requirements.[25]

A recent study of U.S. industrial heating demands concludes that about 7.5 percent of all heat is used at temperatures below 100°C and 28 percent below 288°C. However, direct solar power can be used to pre-heat materials from ambient temperatures to intermediate temperatures before another energy source is employed to achieve the still higher temperature demanded for an industrial process. Such solar pre-heating can play a role in virtually every industrial heat application. If pre-heating is used, 27 percent of all energy for U.S. industrial heat can be delivered under 100° C and about 52 percent under 288° C.[26]

Much of the energy used in the residential, commercial, agricultural, and industrial sectors is employed as low-temperature heat. In the recent past, this demand has been filled by burning fossil fuels at thousands of degrees or nuclear fuels at millions of degrees. Because such energy sources were comparatively cheap, little thought was given to the thermodynamic inefficiency of using them to produce low-grade heat. Now that fuel costs are mounting rapidly, however, demands for heat increasingly will be met directly from the sun.

"A sensible energy strategy demands more than the simple-minded substitution of sunlight for uranium."

Electricity from the Sun

It was long believed that nuclear power would replace the fossil fuels. Because nuclear power is best utilized in centralized electrical power plants, virtually all energy projections therefore show electricity fulfilling a growing fraction of all projected energy demands. Some solar proponents advocate large centralized solar power plants as direct replacements for nuclear power plants to meet this demand. However, solar technologies can provide energy of any quality, and remarkably little of the world's work requires electricity. A sensible energy strategy demands more than the simple-minded substitution of sunlight for uranium.[27]

Electricity now comprises less than 20 percent of energy use in virtually all countries. If energy sources were carefully matched with energy uses, it is difficult to imagine a future society that would need more than one-tenth of its energy budget as electricity—the highest quality and most expensive form of energy. Today, only 11 percent of U.S. energy is used as electricity, and much of this need could be met with other energy sources. To fill genuine needs for electricity, the most attractive technology in many parts of the world will be direct solar conversion.

Two types of large, land-based solar thermal power plants are receiving widespread attention. The "power tower" is currently attracting the most money and minds, although a rival concept—the "solar farm"—is also being investigated. The power tower relies upon a large field of mirrors to focus sunlight on a boiler located on a high structure—the "tower." The mirrors are adjusted to follow the sun across the sky, always maintaining an angle that reflects sunlight back to the boiler. The boiler, in turn, produces high pressure steam to run a turbine to generate electricity. The French, who successfully fed electricity into their national grid from a small tower prototype in January of 1977, plan to have a 10-megawatt unit operating by 1981 and have been aggressively trying to interest the desert nations of the Middle East in this effort. The United States is now testing a small prototype involving a 40-acre mirror field and a 200-watt tower in

New Mexico, and it plans to put a 10-megawatt power plant into operation by 1980 at Barstow, California.

An electric utility in New Mexico plans to combine three 430-foot power towers that generate a total of 50 megawatts with an existing gas-fired power plant at Albuquerque. The proposed complex would utilize the existing generators, turbines, condensers, switchyard etc. The resulting hybrid, which would cost $60 million and cover 170 acres, would have no heat storage capacity; it would simply heat its boilers with gas when the sun failed to shine. A survey by the utility identified 600 existing power plants in the American Southwest (with about 40,000 megawatts of electrical generating capacity) that could be retrofitted with solar power towers.

The "solar farm" concept would employ rows of parabolic reflectors to direct concentrated sunlight onto pipes containing molten salts or hot gases. Special heat exchangers would transfer the 600° C heat from the pipes to storage tanks, filled with melted metal, from whence it could be drawn to generate high pressure steam to run a turbine.

Both the solar farm and the power tower approaches require direct sunlight because their concentrating mirrors cannot use diffuse light. Both will also probably be feasible only in semi-arid regions with few cloudy days and little pollution. One objection raised to such facilities is that they would despoil large tracts of pristine desert. However, proponents point out that the area needed to produce 1,000 megawatts of solar electricity is less than the amount of land that would have to be strip-mined to provide fuel for a similar sized coal plant during its 30-year lifetime and that the solar plant's land could be used forever. In fact, according to Aden and Marjorie Meinel, a 1,000-megawatt solar farm on the Arizona desert would require no more land than must, for safety reasons, be deeded for a nuclear reactor of the same capacity.[28]

Large, centralized solar electric plants consume no finite fuels, produce no nuclear explosives, and hold no ecological punches. With development, such plants should also be economically competitive with fossil-fueled, fission, and fusion power plants. However, they produce only electricity and they are subject to all the problems inherent in centralized high technologies. To the extent that energy needs can be met with lower quality sources or decentralized equipment, the centralized options should be avoided.

As a power source in countries where land is scarce or where cloud cover is frequent, solar electric plants are less promising; efficient long-distance cryogenic electrical transmission may prove feasible but will probably be extremely expensive. Proposals to tap North African deserts for power for Western Europe or to course Mexican sunlight through New York's power grid are therefore unlikely to bear fruit. A more likely consequence of solar thermal-electric development would be the relocation of many energy-intensive industries in sunny climes. In fact, Professor Ignacy Sachs, director of the International Center for Research on Environment and Development in Paris, has predicted that a new solar-powered industrial civilization will emerge in the tropics.

Land-based solar electric plants must bow to one incontrovertible fact: it is always night over half the earth. If such facilities are to generate power after the sun sets, oversized collectors must be built and the excess heat retained in an expensive storage facility until it is needed. But ocean thermal electric conversion (OTEC) plants, which use the ocean as a free collector and storage system, are unaffected by daily cycles. Because the ocean's temperature varies little, OTEC plants can be a source of steady, round-the-clock power.

The temperature difference between the warm surface waters of tropical oceans and the colder waters in the depths is about 20° C. In 1881, J. D'Arsonval suggested in an article in *Revue Scientifique* that this difference could be used to run a closed-cycle engine. In the 1920s, another French scientist, Georges Claude, persuaded the French government to build a number of open-cycle power plants to exploit these ocean thermal gradients. After World War II, the French Government built several OTEC plants (the largest of which had a capacity of 7.5 megawatts) in the hope that such plants would provide inexpensive energy to France's tropical colonies. French interest in the project crumbled along with its overseas empire, but the idea of harnessing ocean thermal gradients to generate power lingers on.[29]

Because of the small temperature differences between deep and surface waters, OTEC's potential efficiency is severely limited. Moreover, as much as a third of the power an OTEC facility produces may be required to pump the enormous amounts of water needed to drive the cycle. Despite these difficulties and the additional problem of transporting power to users on the shore, OTEC proponents contend that the system will be cheap enough to underprice competing sources of electricity. However, this contention is untested, and estimates of an OTEC unit's cost range from about $450 to almost $4,000 per installed kilowatt—excluding the costs of transporting the electricity to the land and the costs of any environmental damages. The real cost will probably fall between these extremes, but early models, at least, will likely veer toward the high end.[30]

The OTEC concept does not involve any new basic technology. Its proponents tend to downplay the technical difficulties as simply matters of "good plumbing," even though the system would require pumps and heat exchangers far larger than any in existence. Because they do not consume any fuel, OTEC systems are largely insured against future cost increases that could affect nuclear or fossil-fueled plants. On the other hand, with so many of their costs as, literally, sunk investments, the viability of OTECs will depend entirely upon their durability and reliability—two open questions at this point. Unexpected vulnerabilities to corrosion, biological fouling, hurricanes, or various other plagues could drive costs up dramatically.

Intensive deployment on the scale urged by OTEC's most ardent advocates could also possibly engender a variety of environmental problems that a few scattered plants would not provoke. An increase in the overall heat of substantial bodies of water and the upwelling of nutrient-rich waters from the ocean bottom could both bring on unfortunate consequences. Ocean temperature shifts could have far-reaching impacts on weather and climate, and displacing deep waters would disturb marine ecology. In addition, physicist Robert Williams of Princeton calculates, the upwelling of carbon-rich water from the ocean bottom could cause atmospheric carbon dioxide to increase substantially.[31] OTECs, like other large centralized sources of electricity, have costs that multiply rapidly when large numbers of plants are built. This technology should probably be limited to a modest number of facilities in ocean areas where conditions are optimal.

The most exciting solar electric prospect is the photovoltaic cell—now the principal power source of space satellites. Such cells generate electricity directly when sunlight falls on them. They have no moving parts, consume no fuel, produce no pollution, operate at environmental temperatures, have long lifetimes, require little maintenance, and can be fashioned from silicon, the second most abundant element in the Earth's crust.[32]

Photovoltaic cells are modular by nature, and little is to be gained by grouping large masses of cells at a single collection site. On the contrary, the technology is most sensibly applied in a decentralized fashion—perhaps incorporated in the roofs of buildings—so that transmission and storage problems can be minimized. With decentralized use, the 80 percent or more of the sunlight that such cells do not convert into electricity can be harnessed to provide energy for space heating and cooling, water heating, and refrigeration.

Fundamental physical constraints limit the theoretical efficiency of photovoltaic cells to under 25 percent. Numerous practical problems force the real efficiency lower—for silicon photovoltaics, the efficiency ceiling is about 20 percent. To obtain maximum efficiency, relatively pure materials with regular crystal structures are required. Such near-perfection is difficult and expensive to obtain. High costs have, in fact, been the principal deterrent to widespread use of photovoltaic cells.

Cost comparisons between photovoltaic systems and conventional systems can be complicated. Solar cells produce electricity only when the sun shines, while conventional power plants are forced to shut down frequently for repairs or maintenance. Depending on the amount of sunlight available where a photovoltaic array is located, the cells might produce between one-fourth and one-half as much power per kilowatt of installed capacity as an average nuclear power plant does. Adding to the costs of photovoltaics is the need for some kind of storage system; on the other hand, the use of photovoltaics may eliminate the need for expensive transmission and distribution systems.

Depending upon who does the figuring, photovoltaic cells now cost between 20 and 40 times as much as conventional sources of base-load electricity. However, as a source of power just during daylight periods of peak demand, photovoltaics cost only four to five times as much as conventional power plants plus distribution systems. Moreover, the costs of conventional power plants have shot steadily upward in recent years while the costs of photovoltaic cells have rapidly declined, and several new approaches are being pursued in an effort to further diminish the costs of photovoltaic arrays. For example, focusing collectors that use inexpensive lenses or mirrors to gather sunlight from a broad area and concentrate it on the cells are being employed. The Winston collector can obtain an eight-to-one concentration ratio without tracking the sun; "tracking" collectors can obtain much higher multiples, but at far greater expense.[33]

Another approach to cutting the costs of photovoltaic cells has been to use less efficient but much cheaper materials than those usually used; amorphous silicon and combinations of cadmium sulfide and copper sulfide are strong candidates. Although the required collector area is thus increased, total costs may be less. Conversely, another approach has been to improve the processing of high-grade materials for photovoltaic cells. Currently, each cell is handcrafted by artisans who use techniques not unlike those employed in a Swiss watch factory. Simple mechanization of this process could lead to large savings. The costs of photovoltaic cells, which amounted to $200,000 per peak kilowatt in 1959, have already fallen to about $13,000 per peak kilowatt and most experts believe that prices will continue to fall rapidly.[34]

Increased production is of paramount importance in lowering the prices of photovoltaics. In an 18-month period of 1975-76, U.S. purchases of photovoltaic cells for earth-bound purposes doubled and the average price per cell dropped by about 50 percent. Price reductions of from 10 to 30 percent for each doubling of output have been common in the electrical components industries, and photovoltaic production should prove no exception to the rule.

The objective of the Low-Cost Silicon Array Project of the U.S. Energy Research and Development Administration is to produce photovoltaics for less than $500 per peak kilowatt, and to produce more than 500 megawatts annually by 1985. This program, contracted through the California Institute of Technology, involves a large number of major corporations. A general consensus appears to be developing among the participants that the goals are reachable and may even be far too modest. Under the auspices of the government's "Project Sunshine," Japan has undertaken a similar research effort.[35]

From a "net energy" perspective, photovoltaics are appealing. Detailed studies of the energy needed to manufacture such cells shows that the energy debt can be paid in less than two years of operation. With more energy-efficient production processes, the energy payback period could, theoretically, be reduced to a matter of weeks. If the energy some cells produce is fed back to produce more cells, photovoltaics can become true energy "breeders"—making more and more energy available each year without consuming any nonrenewable resources. In fact, Malcolm Slesser and Ian Hounam have calculated, an initial one-megawatt investment in photovoltaic cells with a two-year payback period could multiply in 40 years to provide 90 percent of the world's energy needs. These calculations may be a bit optimistic, and the world does not want or need to consume 90 percent of its energy in the form of electricity; but photovoltaics, like other solar technologies, hold up well under net-energy analysis.[36]

A variety of options are available to produce electricity directly from the sun. Several of the approaches sketched here—all of which have been technically demonstrated—are now economically competitive with fossil-fueled plants under some conditions. Prices can be reasonably expected to fall dramatically as more experience is gained. Although solar electricity will probably never be really cheap, it is doubtless worth paying some economic premium for a source of electricity that is safe, dependable, renewable, non-polluting, and—in the case of photovoltaics—highly decentralized.[37]

Catching the Wind

The air that envelopes the Earth functions as a 20-billion-cubic-kilometer storage battery for solar energy. Winds are generated by the uneven heating of our spinning planet's land and water, plains and mountains, equatorial regions and poles. The idea of harnessing this wind to serve human needs may have first occurred to someone watching a leaf skitter across a pond. Five thousand years ago, the Egyptians were already sailing barges along the Nile. Wind-powered vessels of one sort or another dominated shipping until the Nineteenth century, when ships driven by fossil fuels gradually eased them out. A few large cargo schooners plied the waters off the U.S. Atlantic Coast until the 1930s, and the largest windjammers were the greatest wind machines the world has known.[38]

The windmill appears to have originated in Persia two millenia ago. There, vertical shaft devices that turned like merry-go-rounds were used to grind grain and pump water. After the Arab conquest of Persia, wind power spread with Islam throughout the Middle East and to the southern Mediterranean lands. Invading Mongols carried the windmill back to China. Returning crusaders likewise appear to have transferred the technology to Europe—though the tilt (30 degrees to the horizontal) of the axes of early European mills have led some scientists to believe that the device may have been invented independently by a European. Eventually, horizontal-axis windmills with blades that turned like ferris wheels were developed, and they spread throughout Europe.[39]

By the 17th century, the Dutch had a commanding lead in wind technology and were already using wind power to saw wood and make paper. In the late 19th century the mantle of leadership passed to the

"It is doubtless worth paying some economic premium for a source of electricity that is safe, dependable, renewable, and non-polluting."

Danes, who had about 100,000 windmills in operation by 1900. Under the leadership of Poul la Cour, Denmark began making significant investments in wind-generated electricity and by 1916 was operating more than 1,300 wind generators.

The windmill played an important role in American history, especially in the Great Plains, where it was used to pump water. More than six million windmills were built in the United States over the last century; about 150,000 still spin productively. Prior to the large-scale federal commitment to rural electrification in the 1930s and 1940s, windmills supplied much of rural America with its only source of electricity.

After World War I, cheap hydropower and dependable fossil fuels underpriced wind power plants. However, research in many parts of the world continued, and many interesting windmill prototypes were constructed. In 1931, the Soviet Union built the world's first large wind generator near Yalta. Overlooking the Black Sea, this 100-kilowatt turbine produced about 280,000 kilowatt-hours of electricity per year. In the 1950s, Great Britain built two 100-kilowatt turbines. In 1957, Denmark built a 200-kilowatt turbine, and France constructed an 800-kilowatt wind generator. In 1963, a 1,000-kilowatt wind turbine was built in France.

The largest wind generator ever built was the 1,250-kilowatt Grandpa's Knob machine designed by Palmer Putnam and erected on a mountain top in central Vermont. It began generating electricity on August 29, 1941, just two years after its conception. However, the manufacturer had been forced to cut corners in his haste to finish construction before the icy hand of war-time rationing closed upon the project, and the eight-ton propeller blades developed stress cracks around their rivet holes. Although the cracking was noticed early, the blades could not be replaced because of materials shortages. Finally, a blade split, spun 750 feet in the air, and brought the experiment to a crashing conclusion. The private manufacturer had invested more than one million dollars in the project and could afford to risk no more.[40]

Despite the enthusiasm of occasional wind-power champions in the federal government, no more major wind generators were constructed in the United States until 1975. Then, NASA began operating a 100-kilowatt prototype near Sandusky, Ohio, that resembles a huge helicopter mounted sideways atop a transmission tower. The next major step in the American program will be a 1,500-kilowatt wind turbine to be built jointly by General Electric and United Technology Corporation by 1978.

Before the GE-UTC turbine begins operating, however, it may have slipped into second place in the size sweepstakes. Tvind, a Danish college, has nearly completed a 2,000-kilowatt wind turbine, at a cost of only $350,000. (Doubtless the most important factor in holding down expenses for the Tvind generator is that the college staff paid for the project out of their own pockets. If successful, Tvind will hearten those who hope that major technical accomplishments can still be achieved without reliance on central governments or big business.)[41]

The Tvind wind machine, like virtually all large wind turbines today, will have only two blades. While more blades provide more torque in low-speed winds (making multiple blades particularly useful for purposes such as small-scale water pumping), fewer blades capture more energy for their cost in faster winds. A two-blade propeller can extract most of the available energy from a large vertical area without filling the area with metal that could crack or split in a storm.

Since power production increases with the square of a turbine's size, large wind machines produce far more energy than do small ones. Moreover, wind power increases as the cube of velocity, so a 10-meter-per-second wind produces eight times as much power as a 5-meter-per-second breeze does. Consequently, some wind power enthusiasts limit their dreams to huge turbines on very windy sites. In particular, a recent survey of large U.S. corporations conducting wind power research disclosed that only one company had any interest in small or intermediate sized turbines.[42]

However, the "think big" approach does not necessarily make sense. The crucial question for windmills is how much energy is harnessed per dollar of investment. Increases in output are desirable only if the value of the additional energy extracted exceeds the extra cost, and economic optimization does not necessarily lead to the construction of giant turbines. Smaller windmills might lend themselves more easily to mass production and might be easier to locate close to the end-user (thus reducing transmission costs). Small windmills can produce power in much lower winds than large ones do and can thus operate more over a given time. Smaller-scale equipment also allows a greater decentralization of ownership and control, and the consequences of equipment failure are not likely to be catastrophic. Finally, wind turbine development will probably be constrained by practical limits on propeller size. Large turbines place great stresses on both the blade and tower, and all giant turbines built to date have suffered from metal fatigue.

On a small scale, wind power can be cheaply harnessed to perform many kinds of work. The Valley of Lasithi on Crete uses an estimated 10,000 windmills, which catch the wind in triangular bands of white sail cloth, to pump irrigation water. Similar windmills built of local materials have recently been erected in East Africa. The New Alchemy Institute in Massachusetts, working with the Indian Institute of Agricultural Research and the Indian National Aeronautical Laboratory, has developed a 25-foot sailwing pump for rural use; employing the wheel of a bullock cart as the hub and a bamboo frame for the cloth sails, this simple machine could provide cheap power to Indian villages. The Brace Research Institute in Canada has designed a Savonius water pump that can be constructed from two 45-gallon oil drums cut in half. Already used in the Caribbean, the device costs about $50 to make and will operate at wind speeds as low as 8 mph.

Traditionally, wind has been used primarily to pump water and to grind grain. Windmills can also produce heat that can be stored and used later in space heating, crop drying, or manufacturing processes. A particularly attractive new approach is to compress air with wind turbines. Pressurized air can be stored much more easily than electricity, a fact to which virtually every gasoline station in the United

States attests. Stored air can either be used as needed to directly power mechanical equipment or released through a turbine to generate electricity. On a large scale, pressurized air can be stored in underground caverns.

The modern wind enthusiast can choose from many options: multiple-blade propellers, triple-blade props, double-blade props, single-blade versions with counterweights, sailwings, cross-wind paddles, and gyromills. In some wind turbines, the propeller is upwind from the platform, while in others it is located downwind. Some platforms support single large turbines; others support many small ones. A machine with two sets of blades turning in opposite directions is being tested in West Germany.[43]

One of the most interesting multiple-blade devices for small and moderate sized generators is under development at Oklahoma State University. This mill resembles a huge bicycle tire, with flat aluminum blades radiating from the hub like so many spokes. Instead of gearing the generator to the hub of the windmill, the Oklahoma State machine operates on the principle of the spinning wheel: the generator is connected to a belt that encircles the faster-moving outer rim.

The Darrieus wind generator, favored by the National Research Council of Canada and by Sandia Laboratories in New Mexico, looks like an upside-down egg beater, and turns around its vertical axis like a spinning coin. The Darrieus holds several striking advantages over horizontal axis turbines: it will rotate regardless of wind direction; it does not require blade adjustments for different wind speeds; and it can operate without an expensive tower to provide rotor clearance from the ground. Aerodynamically efficient and light-weight, the Darrieus might cost as little as one-sixth as much as a horizontal-shaft windmill of the same capacity. In early 1977, a 200-kilowatt Canadian Darrieus wind turbine began feeding electricity into the 24,000-kilowatt power grid that serves the Magdalen Islands in the Gulf of St. Lawrence. If this machine lives up to its economic potential, other Darrieus turbines will be installed.[44]

Intriguing new approaches to wind power may well be gestating. Little money or effort has been put into wind turbine research over the last two decades, although aeronautical engineering has made enormous strides over the same period. With interest in wind machines gathering force, new approaches could soon emerge. For example, a "confined vortex" generator being developed by James Yen steers wind through a circular tower, creating a small tornado-like effect; this generator utilizes the difference in pressure between the center of the swirling wind and the outside air to drive a turbine.[45] Large amounts of electricity could, theoretically, be generated by relatively small turbines of this type. The U.S. Energy Research and Development Administration recently awarded Dr. Yen $200,000 to develop this idea further. However, the viability of wind power does not depend upon scientific breakthroughs; existing wind technologies can compete on their own terms for a substantial share of the world's future energy budget.

Estimating the probable cost of wind power is a somewhat speculative undertaking. The cost of generating electricity with the wind can be measured in two different ways—depending upon whether the system provides "base load" power or only supplementary power. If wind generators feed power directly into a grid when the wind blows, and if other generating facilities have to be constructed to handle peak loads when the wind isn't blowing, the average costs of building and maintaining such windmills must compete with merely the cost of fuel for the alternative power plant. Obviously, this calculation hinges not only on how much a windmill costs to construct, but also on how long it lasts and how reliably it functions. Conclusions are premature until experience has been gained, but many studies have suggested that intermittent electricity could be generated today from the wind for considerably less than the cost of providing fuel for an existing oil-fired unit. Moreover, wind power costs could diminish significantly as more experience is acquired, while oil costs will certainly rise.[46]

If wind is to be used to provide constant, reliable power, then the cost of building a wind generator plus a storage facility must not exceed the total cost (including the environmental cost) of building and operating a conventional power plant. Used in conjunction with a hydro-electric facility with reserve capacity, wind turbines should already have a substantial cost advantage over conventional power plants. For other storage set-ups, cost calculations remain unsubstantiated, but studies of analogous technologies suggest that such base-load wind systems will be economically sound. When social and environmental costs are included, the case becomes even stronger. Accordingly, such systems should now be built and operated so that these calculations can be proven.

The rate and extent to which wind power is put to work is much more likely to be a function of political considerations than of technical or economic limits. The World Meteorological Organization has estimated that 20 million megawatts of wind power can be commercially tapped at the choicest sites around the world, not including the possible contributions from large clusters of windmills at sea.[47] By comparison, the current total world electrical generating capacity is about one-and-one-half million megawatts. Even allowing for the intermittent nature of the resource, wind availability will not limit wind power development. Long before a large fraction of the wind's power is reaped, capital constraints and social objections will impose limits on the growth of wind power.

Well-designed, well-placed wind turbines will achieve a high net energy output with an exceptionally mild environmental and climatic impact: wind machines produce no pollution, no hazardous materials, and little noise. In fact, the principal environmental consequences of wind power will be the comparatively modest ones associated with mining and refining the metals needed for wind turbine construction —ill effects associated with virtually every energy source. Windmills will have to be kept out of the migratory flyways of birds, but these routes are well-known and can be easily avoided. Where aesthetic objections to the use of wind technology arise, windmills could be located out of the visual range of populated areas, even a few miles out to sea. Moreover, some wind machines, such as the Darrieus, strike many as handsome. All things considered, a cleaner, safer, less disruptive source of energy is hard to imagine.[48]

"The rate and extent to which wind power is put to work is much more likely to be a function of political considerations than of technical or economic limits."

Falling Water

Numerous surveys of the world's water-power resources suggest that a potential of about three million megawatts exists, of which about one-tenth is now developed. The figure is unrealistic, however, since reaching the three-million-megawatt potential would require flooding fertile agricultural bottomlands and rich natural ecosystems. On the other hand, none of the surveys include the world's vast assortment of small hydro-electric sites. By even the most conservative standards, potential hydropower developments definitely exceed one million megawatts, while current world hydro-electric capacity is only 340 thousand megawatts.

Industrialized regions contain about 30 percent of the world's hydro-electric potential as measured by conventional criteria but produce about 80 percent of all its hydro-electricity. North America produces about one-third, Europe just a little less, and the Soviet Union about one-tenth. Japan, with only 1 percent of the world's potential, produces over 6 percent of global hydro-electricity. In contrast, Africa is blessed with 22 percent of all hydro-electric potential, but produces only 2 percent of all hydro-electricity—half of which comes from the Aswan High Dam in Egypt, the Akosombo Dam in Ghana, and the Kariba Dam on the Zambesi River between Zambia and Rhodesia. Asia (excluding Japan and the USSR) has 27 percent of the potential resources, and currently generates about 12 percent of the world's hydro-electricity; most of its potential lies in the streams that drain the Tibetan Plateau, at sites far from existing energy markets. Latin America, with about 20 percent of the world's total water-power resources, contributes about 6 percent of the current world output. Nine of the world's 15 most powerful rivers are in Asia, three are in South America, two are in North America, and one is in Africa.[49]

The amount of hydropower available in a body of moving water is determined by the volume of water and by the distance the water falls. A small amount of water dropping from a great height can produce as much power as a large amount of water falling a shorter distance. The Amazon carries five times as much water to the sea as does the world's second largest river, the Congo; but because of the more favorable topography of its basin, the Congo has more hydro-electric

potential. In mountainous headwater areas, such as Nepal, where relatively small volumes of water fall great distances, numerous choice sites exist for stations of up to 100 megawatts each.[50]

Used by the Romans to grind grain, water wheels reached their highest pre-electric form in the mid-1700s with the development of the turbine wheel. The Versailles waterworks produced about 56 kilowatts of mechanical power in the 18th century. In 1882, the first small hydro-electric facility began producing 125 kilowatts of electricity in Appleton, Wisconsin; and, by 1925, hydropower accounted for 40 percent of the world's electric power. Although hydro-electric capacity has since grown 15-fold, its share of the world's electricity market has fallen to about 23 percent.

Early hydro-electric development tended to involve small facilities in mountainous regions. In the 1930s, emphasis shifted to major dams and reservoirs in the middle and lower sections of rivers, such as the Tennessee Valley dams in the United States and the Volga River dams in the Soviet Union. The world now has 64 hydroplants with capacities of 1,000 megawatts or more each: the Soviet Union has 16, the United States has 12, Canada has 11 (the U.S. and Canada share another), and Brazil has 10.

The environmental and social problems associated with huge dams and reservoirs far outweigh those surrounding small-scale installations or projects that use river diversion techniques. Moreover, the increments by which small facilities boost a region's power supply are manageable. In contrast, a tripling or quadrupling of a power supply in one fell swoop by a giant dam can lead to a desperate search for energy-intensive industries to purchase surplus power, dramatically upsetting the politics and culture of an area.

Much of the extensive hydro-electric development in Japan, Switzerland, and Sweden has entailed use of comparatively small facilities, and such small units hold continuing promise for developing countries. In late 1975, China reportedly had 60,000 small facilities that together generated over two million kilowatts—about 20 percent of China's total hydro-electric capacity. The Chinese facilities are located in sparsely populated areas to which sending electricity from huge centralized facilities would involve prohibitive transmission costs. Local workers build the small earth-filled or rock-filled dams that provide substantial flood control and irrigation benefits as they bring power to the people.[51]

Nevertheless, building enormous facilities to capture as much power as possible while taking advantage of the economies of large scale is tempting. Although this approach has been used extensively and rather successfully in temperate zones, many of the remaining prime locations are in the tropics, where troubles may arise. The Congo, for example, with a flow of 40,000 cubic meters per second and a drop of nearly 300 meters in the final 200 kilometers of its journey to the ocean, has an underdeveloped hydro-electric potential of 30,000 megawatts. But experience in other warm areas indicates that great care must be taken in exploiting such resources.

The Aswan High Dam provides a textbook case of the problems that can encumber a major hydro-electric development in the tropics. So trouble-ridden is Aswan that its costs largely offset its benefits. Although Aswan is a source of electricity, of flood and drought control, and of irrigation, the dam's users and uses sometimes conflict. For example, Aswan provides more than 50 percent of Egypt's electrical power, but its production is highly seasonal; during winter months, the flow of water through the dam is severely diminished while irrigation canals are cleaned. This reduced flow causes power generation to drop from a designed capacity of 2,000 megawatts to a mere 700 megawatts. Furthermore, lack of money for an extensive transmission grid has meant that electricity does not reach many of the rural villages that had hoped to benefit from the project.

Aswan saved Egypt's rice and cotton crops during the droughts in northeastern Africa in 1972 and 1973. Irrigation has increased food production by bringing approximately 750,000 formerly barren acres under cultivation, and by allowing farmers to plant multiple crops on a million acres that had previously been harvested only once a year. These timely boosts have enabled Egypt's food production to keep pace, though just barely, with its rapidly growing population. On the other hand, the dam has halted the natural flow of nutrient-rich silt, leaving downstream farmers to rely increasingly upon energy-intensive chemical fertilizers; and the newly irrigated areas are so plagued by waterlogging and mounting soil salinity that a $30-million drainage program is now needed. In addition, the canals in some areas rapidly clog with fast-growing water hyacinths.

The Aswan has also given a new lease to an age-old health hazard in Egypt. Schistosomiasis, a disease caused by parasitic worms carried by water snails, has long been endemic in the Nile delta where most of Egypt's population is concentrated, but in the past it was rarely found in upstream areas. Since the construction of the large dam, infestations of this chronic and debilitating affliction are also common along the Nile and its irrigation capillaries in Upper Egypt. Many of the major problems associated with Aswan should have been anticipated and avoided. Even now, Aswan's worst problems probably can be either solved or managed. But after-the-fact remedies will be costlier and less effective than a modest preventative effort would have been.

The inevitable siltation of reservoirs does more to spoil the use of dams as renewable energy sources than does any other problem. Siltation is a complex phenomenon that hinges upon several factors, one of which is the size of the reservoir. For example, the Tarbela Reservoir in Pakistan holds only about one-seventh the annual flow of the Indus, while Lake Mead on the Colorado can retain two years' flow. The life expectancy of the Tarbela is measurable in decades; Lake Mead will last for centuries. The rate of natural erosion, another factor in siltation, is determined primarily by the local terrain. Some large dams in stable terrains have a life expectancy of thousands of years; others have been known to lose virtually their entire storage capacity during one bad storm. Logging and farming can greatly accelerate natural erosion too; many reservoirs will fill with silt during one-fourth their expected life spans because these and other human activities ruin their watersheds.

"The greatest potential for future hydropower development lies in those lands that are currently most starved for energy."

Siltation, which affects the dam's storage capacity but not its power generating capacity, can be minimized. Water can be sluiced periodically through gates in the dam, carrying with it some of the accumulated silt. Reservoirs can be dredged, though at astronomical costs. By far the most effective technique for handling siltation is lowering the rate of upstream erosion through reforestation projects and enlightened land use.[52]

Dams cannot be evaluated apart from their interaction with many other natural and artificial systems. They are just one component, albeit a vital one, of river basin management. Locks will have to be provided on navigable rivers, and fish ladders (one of the earliest victories of environmentalists) must be installed where dams block the spawning routes of anadromous fish. If a dam is located in a dry area, power generation must be coordinated with downstream irrigation needs. If a populated basin is to be flooded, the many needs of displaced people as well as the loss of fertile bottomland must be taken into account. Unpopulated basins are politically easier to dam, but in unsettled areas care must nevertheless be taken to preserve unique ecosystems and other irreplaceable resources.

Dams are vulnerable to natural forces, human error, and acts of war. The 1976 collapses of the Bolan Dam in Pakistan, the Teton Dam in Idaho, and a large earthen dam outside La Paz on Mexico's Baja Peninsula serve as emphatic reminders of the need for careful geological studies and the highest standards of construction.

Dams recommend themselves over most other energy sources. They provide many benefits unconnected to power production; they are clean; and their use does not entail the storage problems that plague so many other renewable sources. Indeed, using dams as storage mechanisms may be the most effective way to fill in the gaps left by solar and wind power. In addition, the conversion of water power into electrical power is highly efficient—85 percent or more. Finally, dams can be instruments of economic equity; the greatest potential for future hydropower development lies in those lands that are currently most starved for energy.

Plant Power

Green plants began collecting and storing sunshine more than two billion years ago. They photosynthesize an estimated one-tenth of one percent of all solar energy that strikes the earth. Somewhat more than half of this fraction is spent on plant metabolism; the remainder is stored in chemical bonds and can be put to work by human beings.

All fossil fuels were once biomass, and the prospect of dramatically shortening the time geological forces take to convert vegetation into oil, gas, and coal (roughly a third of a billion years) now intrigues many thoughtful persons. Dry cellulose has an average energy content of about four kilocalories per gram—60 percent as much as bituminous coal, and the hydrocarbons produced by certain plants contain more energy than coal does. Biomass can be transformed directly into substitutes for some of our most rapidly vanishing fuels.

Because green plants can be grown almost everywhere, they are not very susceptible to international political pressures. Unlike fossil fuels, botanical energy resources are renewable. In addition, biomass operations involve few of the environmental drawbacks associated with the large-scale use of coal and oil.

The ultimate magnitude of this energy resource has not been established. Measuring the earth's total photosynthetic capacity poses difficulties, and estimates vary considerably. Most experts peg the energy content of all annual biomass production at between 15 and 20 times the amount humans currently get from commercial energy sources, although other estimates range from 10 to 40 times.[53] Using all the vegetation that grows on Earth annually as fuel is unthinkable. But the energy that could reasonably be harvested from organic sources each year probably exceeds the energy content of all the fossil fuels currently consumed annually.

Two important caveats must be attached to this statement. The first qualification concerns conversion efficiency. Much of the energy bound in biomass will be lost during its conversion to useful fuels. These losses, however, need be no greater than those involved in converting coal into synthetic oil and gas. The second catch is geographical: the areas with the greatest biomass production are wet equatorial regions—not the temperate lands where fuel use is highest today. The full biological energy potential of the United States, calculated liberally, probably amounts to about one-fifth of current commercial energy use; in contrast, the potential in many tropical countries is much higher than their current fuel consumption levels. However, many equatorial nations will be hard-pressed to secure the capital and to develop the technology needed to use their potential plant power.[54]

Organic fuels fall into two broad categories: waste from non-energy processes (such as food and paper production) and crops grown explicitly for their energy value. Since waste disposal is unavoidable and often costly, converting waste into fuels—the first option—is a sensible alternative to using valuable land for garbage dumps. However, the task of waste collection and disposal usually falls to those who cling to the bottom rungs of the economic and social ladder and, until recently, waste seldom attracted either the interest of the well-educated or the investment dollars of the well-heeled. But change is afoot, partly because solid waste is now often viewed as a source of abundant high-grade fuel that is close to major energy markets.

The wastes easiest to tap for fuels may be those that come from food production. Bagasse, the residue from sugar cane, has long been used as fuel in most cane-growing regions. Corn stalks and spoiled grain are being eyed as potential sources of energy in the American Midwest. And India's brightest hope for bringing commercial energy to most of its 600,000 villages is pinned to a device that produces methane from excrement and that leaves fertilizer as a residue.

Agricultural residues—the inedible, unharvested portions of food crops—represent the largest potential source of energy from waste. But most plant residues are sparsely distributed, and some cannot be spared: they are needed to feed livestock, retard erosion, and enrich the soil. Yet, wisely used, field residues can guard the soil, provide animal fodder, *and* serve as a fuel source.

Agricultural energy demands are highly seasonal, and usage peaks do not always coincide with the periods during which residue-derived energy is most plentiful. In agricultural systems still largely dependent upon draft animals, this problem is minimized: silage and hay can easily be stored until needed. On mechanized farms, energy storage poses a somewhat more difficult problem.

Animal excrement is another potentially valuable source of energy. Much undigested energy remains bound in animal excrement; and cattle feedlots, chicken coops, and pig sties could easily become energy farms. Indeed, animal dung has been burned in some parts of the world for centuries; in the United States, buffalo chips once provided cooking fuel to frontiersmen on the treeless Great Plains. In India today, about 68 million tons of dry cow dung are burned as fuel each year, mostly in rural areas, although more than 90 percent of the potential heat and virtually all the nutrients in excrement are lost in inefficient burning.[55] Far more work could be obtained from dung if it were first digested to produce methane gas; moreover, all the nutrients originally in the dung could then be returned to the soil as fertilizer.[56]

In May 1976, Calorific Recovery Anaerobic Process Inc., (CRAP), of Oklahoma City received Federal Power Commission authorization to provide the Natural Gas Pipeline Company annually with 820 million cubic feet of methane derived from feedlot wastes. Other similar proposals are being advanced. Although most commercial biogas plants planned in the United States are associated with giant feedlots, a more sensible long-term strategy might be to range-feed cattle as long as possible and then to fatten them up, a thousand at a time, on farms in the midwestern grain-belt. Cow dung could power the farm and provide surplus methane, and the residue could be used as fertilizer. In addition, methane generation has been found to be economically attractive in most dairies—an important point since more than half of all U.S. cows are used for milk production.[57]

Collectible crop residues and feedlot wastes in the United States contain 4.6 quadrillion Btus (quads)—more energy than all the nation's farmers use. Generating methane from such residues is often economical. However, developing a farm that is totally energy self-sufficient may require a broader goal than maximizing short-term food output.[58]

Human sewage, too, contains a large store of energy. In some rural areas, particularly in China and India, ambitious programs to produce gaseous fuel from human and animal wastes are under way. Unfortunately, toxic industrial effluents are now mixed with human waste in many of the industrialized world's sewage systems, and these pollutants make clean energy-recovery vastly more difficult. If these pollutants were kept separate, a large new energy source would become available.

The residues of the lumber and paper industries also contain usable energy. A study conducted for the Ford Foundation's Energy Policy Project found that if the U.S. paper industry were to adopt the most energy-efficient technologies now available and were to use its wood wastes as fuel, fossil fuel consumption could be reduced by a staggering 75 percent. The Weyerhaeuser Company recently announced a $75 million program to expand the use of wood waste as fuel for its paper mills; "We're getting out of oil and gas wherever we can," commented George Weyerhaeuser, the company's president. Sweden already obtains 7 percent of its total energy budget by exploiting wastes of its huge forest-products industry.

Eventually, most paper becomes urban trash. Ideally, much of it should instead be recycled—a process that would save trees, energy, and money. But unrecycled paper, along with rotten vegetables, cotton rags, and other organic garbage, contains energy that can be economically recaptured. Milan, Italy runs its trolleys and electric buses partly on power produced from trash. Baltimore, Maryland expects to heat much of its downtown business district soon with fuel obtained by distilling 1,000 tons of garbage a day.

American waste streams alone could, after conversion losses are subtracted, produce nearly five quads per year of methane and "charoil" —about 7 percent of the current U.S. energy budget. Decentralized agrarian societies could derive a far higher percentage of their commercial energy needs from agricultural, forest, and urban wastes.

The second plant-energy option, the production of "energy crops," will probably be limited to marginal lands, since worldwide population pressures are already relentlessly pushing food producers onto lands ill-suited to conventional agriculture. Yet, much potential energy cropland does exist in areas where food production cannot be sustained. Some prime agricultural land could also be employed during the off-season to grow energy crops. For example, winter rye (which has little forage value) could be planted in the American Midwest after the fall corn harvest and harvested for energy in the spring before maize is sowed.

Factors other than land scarcity limit biomass growth. The unavailability of nutrients and of an adequate water supply are two. Much marginal land is exceedingly dry, and lumber and paper industries will make large demands on areas wet enough to support trees. The energy costs of irrigating arid lands can be enormous, reducing the net energy output dramatically.

Yields from energy crops will reflect the amount of sunlight such crops receive, the acreage devoted to collecting energy, and the efficiency with which sunlight is captured, stored, harvested, transported, and put to work. Ultimately, they will also depend upon our ability to produce crops that do not sap the land's productivity and that can resist common diseases, pests, fire, and harsh weather.

The most familiar energy crop, of course, is firewood. A good fuel tree has a high annual yield when densely planted, resprouts from cut stumps (coppices), thrives with only short rotation periods, and is generally hardy. Favored species for fuel trees are eucalyptus, sycamore, and poplar—an intelligently planned tree plantation would probably grow a mixture of species.

Forests canopy about one-tenth of the planet's surface and represent about half the earth's captured biomass energy.[59] A century ago, the United States obtained three-fourths of its commercial energy

"Forests canopy about one-fourth of the planet's surface and represent about half the earth's captured biomass energy."

from wood. In the industrialized world today, only a small number of the rural poor and a handful of self-styled rustics rely upon fuel wood. However, the case is emphatically different in the Third World. Thirty percent of India's energy, and 96 percent of Tanzania's comes from wood.[60] In all, about half the trees cut down around the world are burned to cook food and to warm homes.

In many lands, unfortunately, humans are propagating faster than trees. Although much attention has been paid to the population-food equation, scant notice has been given to the question of how the growing numbers will cook their food. As desperate people clear the land of mature trees and saplings alike, landscapes become barren; and, where watersheds are stripped, increasingly severe flooding occurs. In the parched wastelands of north central Africa and the fragile mountain environments of the Andes and the Himalayas, the worsening shortage of firewood is today's most pressing energy crisis.[61]

A variety of partial solutions have been suggested for the "firewood crisis." In southern Saudi Arabia, some tribes impose the same penalty for the unauthorized cutting of a tree as for the taking of a human life. China has embarked upon an ambitious reforestation program, and many other nations are following suit. Some forestry experts advocate substituting fast-growing trees for native varieties as a means of keeping up with demand.[62] However, the vulnerability of forests of genetically similar trees to diseases and pests calls the application of such agricultural techniques to silviculture into question.

Improving the efficiency with which wood is used would also help alleviate the firewood shortage. In India, using firewood for cooking is typically less than 9 percent efficient. The widespread use of downdraft wood-burning stoves made of cast iron could, S. B. Richardson estimates, cut northern China's fuel requirements for heating and cooking by half.[63] Other efficient wood-burning devices can be made by local labor with local materials.

Wood can be put to more sophisticated uses than cooking and space heating. It can fuel boilers to produce electricity, industrial process steam, or both. The size of many prospective tree-harvesting operations (about 800 tons per day) is well tailored to many industrial energy needs. Decentralized co-generation using wood would also fit in well with current worldwide efforts to move major industries away from urban areas. In particular, the creation of forest "plantations" to produce fuel for large power plants at a cost comparable to that of coal has been recommended.[64] However, some researchers argue that the cost of transporting bulk biomass should lead us to think in terms of energy "farms" of a few thousand hectares or less.[65]

Trees are not the only energy crops worth considering. A number of other land and water crops have their advocates among bioconversion specialists. Land plants with potential as energy sources include sugarcane, cassava (manioc), and sunflowers, as well as some sorghums, kenaf, and forage grasses. Among the more intriguing plants under consideration are *Euphorbia lathrus* and *Euphorbia tirncalli,* shrubs whose sap contains an emulsion of hydrocarbons in water. While other plants also produce hydrocarbons directly, those produced by *Euphorbia* resemble the constituents in petroleum. Such plants might, Nobel laureate Melvin Calvin estimates, produce the equivalent of 10 to 50 barrels of oil per acre per year at a cost of $10 or less per barrel. Moreover, *Euphorbia* thrives on dry, marginal land.[66]

Several different crops could be cultivated simultaneously, a report by the Stanford Research Institute suggests, and side-by-side cropping could allow year-round harvesting in many parts of the world. Such mixed cropping would also increase ecological diversity, minimize soil depletion, and lower the vulnerability of energy crops to natural and human threats.[67]

Enthusiastic reports by NASA National Space Technology Laboratories have focused attention on the energy potential in water hyacinths. Thought to have originated in Brazil, the fast-growing water hyacinth now thrives in more than 50 countries; it flourishes in the Mississippi, Ganges, Zambezi, Congo, and Mekong rivers, as well as in remote irrigation canals and drainage ditches around the world. The government of Sudan is experimenting with the anaerobic digestion of thousands of tons of hyacinths mechanically harvested from the White Nile. However, a recent Battelle Laboratory report discounts the potential commercial importance of water hyacinths in the United States, in part because of their winter dormancy.[68]

Algae is another potential fuel. Some common types of this scummy, nonvascular plant have phenomenal growth rates. However, current harvesting techniques require large inputs of energy, the use of which lowers the net energy output of algae farming. Although solar drying would improve the energy balance, engineering breakthroughs are needed before impressive net energy yields can be obtained.

One of the more fascinating proposals for raising energy crops calls for the cultivation of giant seaweed in the ocean. As Dr. Howard Wilcox, manager of the Ocean Farm Project of the U.S. Naval Undersea Center in San Diego, points out, "most of the earth's solar energy falls at sea, because the oceans cover some 71 percent of the surface area of the globe." The Ocean Farm Project, an effort to cultivate giant California kelp to capture some of this energy through photosynthesis, presently covers a quarter-acre. But the experimental operation will, Wilcox hopes, eventually be replaced by an ocean farm 470 miles square. Such a sea field could, theoretically, produce as much natural gas as the U.S. currently consumes.[69]

Biomass can be transformed into useful fuels in many ways, some of which were developed by the Germans during the petroleum shortages of World War II. Although one-third to two-thirds of the energy in biomass is lost in most conversion processes, the converted fuels can be used much more efficiently than raw biomass. The principal technologies now being explored are direct combustion, anaerobic digestion, pyrolysis, hydrolysis, hydrogasification, and hydrogenation.

In the industrialized world, organic energy is often recovered by burning urban refuse. To produce industrial process steam or electricity or both, several combustion technologies can be employed: waterwall incinerators, slagging incinerators, and incinerator turbines. Biomass can also be mixed with fossil fuels in conventional boilers, while fluidized-bed boilers can be used to burn such diverse substances as lumber mill wastes, straw, corn cobs, nutshells, and municipal wastes.

Since trash piles up menacingly in much of the urban world, cities can afford to pay a premium for energy-generating processes that reduce the volume of such waste. Urban trash lacks the consistency of coal, but its low sulfur content makes it an attractive energy source environmentally. Following the lead set by Paris and Copenhagen 50 years ago, several cities now mix garbage with other kinds of power-plant fuel to reduce their solid waste volume, to recover useful energy, and to lower the average sulfur content of their fuel. A $35 million plant in Saugus, Massachusetts burns garbage from 12 towns, producing steam that is then sold to a nearby General Electric factory that hopes to save 73,000 gallons of fuel oil per day on its new fuel diet.

The next easiest method of energy recovery is anaerobic digestion—a fermenting process performed by a mixture of micro-organisms in the absence of oxygen. In anaerobic digestion, acid-forming bacteria convert wastes into fatty acids, alcohols, and aldehydes; then, methane-forming bacteria convert the acids to biogas. All biomass except wood can be anaerobically digested, and the process has been recommended for use in breaking down agricultural residues and urban refuse.[71] Anaerobic digestion takes place in a water slurry, and the process requires neither great quantities of energy nor exotic ingredients. Anaerobically digested, the dung from one cow will produce an average of ten cubic feet of biogas per day—about enough to meet the daily cooking requirements of a typical Indian villager.

Many developing and some industrial nations are returning to this old technology, anaerobic digestion, for a new source of energy. Biogas generators convert cow dung, human excrement, and inedible agricultural residues into a mixture of methane and carbon dioxide that also contains traces of nitrogen, hydrogen, and hydrogen sulfide. Thirty thousand small biogas plants dot the Republic of Korea; and the People's Republic of China claims to have about two million biogas plants in operation.[70]

India has pioneered efforts to tailor biogas conversion to small-scale operations. After the OPEC price increases of 1973, annual gobar (the Hindi word for cow dung) gas plant sales shot up first to 6,560 and then to 13,000. In 1976, sales numbered 25,000. "We've reached take-off," says H. R. Srinivasan, the program's director. "There's no stopping us now."

In addition to methane, other products can be derived from the biogasification of animal wastes and sewage. The residue of combustion is a rich fertilizer that retains all the original nutrients of the biomass and that also helps the soil retain water in dry periods. At Aurobindo Ashram in Pondicherry, India, wastes from cows, pigs, goats, and chickens will be gasified; the residue will be piped into ponds supporting algae, aquatic plants, and fish grown for use as animal fodder; and treated effluents from the ponds will be used to irrigate and fertilize vegetable gardens. Experience with biogas plants in "integrated farming systems" in Papua-New Guinea suggests that the byproducts of such controlled processes can be even more valuable than the methane.[72]

In developing countries, decentralized biological energy systems like that planned in Pondicherry could trigger positive social change. For small, remote villages with no prospects of getting electricity from central power plants, biogas can provide relatively inexpensive, high-grade energy and fertilizer. Ram Bux Singh, a prominent Indian developer and proponent of gobar gas plants, estimates that a small five-cow plant will repay its investment in just four years.[73] Larger plants serving whole villages are even more economically enticing. However, where capital is scarce, the initial investment is often difficult to obtain. In India, the Khadi and Village Industries Commission promotes gobar plant construction by granting subsidies and low-interest loans. The Commission underwrites one-fifth of the cost of individual plants and one-third of the cost of community plants. In the poorer areas, the Commission pays up to 100 percent of the cost of cooperative plants.

In efforts to hold down the cost of gobar plants and to conserve both scarce steel and cement in developing lands, researchers are producing new materials for use in digester construction. For example, a large cylindrical bag, reinforced with nylon and equipped with a plastic inlet and outlet, can be installed in a hole in the ground and weighted down in about one hour. The total cost can be as little as 15 percent of that of conventional digesters. Other experimental models are now being made out of natural rubber, mud bricks, bamboo pipes, and various indigenous hardwoods. In general, the ideal biogas plant for poor rural communities would be labor-intensive to build and operate and would be constructed of local materials.

The principal problem plaguing Third World biogas plants are temperature shifts, which can slow down or halt digestion. Low temperatures are particularly troublesome in Korea and China, where gas production slumps in winter when energy demands are highest. Possible remedies include improving insulation, burying future facilities to take advantage of subterranean heat, and erecting vinyl or glass greenhouses over the digesters to trap solar energy for heating. Alternatively, some of the gas produced in the digester could be used to heat the apparatus itself.

Alan Poole, a bioconversion specialist with the Institute for Energy Analysis at Oak Ridge, estimates that methane produced at the rate of 100 tons per day in a U.S. biogas plant would cost less than $4.00 per million Btu's, which approximates the expected cost of deriving commercial methane from coal.[74] In industrial countries, however, the recent trend has been away from anaerobic digestion. In 1963, this process was utilized in 70 percent of the U.S. wastewater treatment plants, but today it is being replaced—especially in smaller cities and towns—by processes that use more energy than they produce. The switch, which is now taking place at a capital cost in excess of $4 billion annually, was prompted largely by digester failures. Although poor design and operator error can both lead to pH imbalances or temperature fluctuations, the principal cause of unreliability appears to be the presence of inhibitory materials—especially heavy metals, synthetic detergents, and other industrial effluents.

These same industrial contaminants can also cause serious problems if the digested residues are used as fertilizer in agriculture. Some of these inhibitory substances can be separated routinely, but some will have to be cut off at the source and fed into a different treatment process if excrement is to be anaerobically digested.

Anaerobic digestion produces a mixture of gases, only one of which —methane—is of value. For many purposes, the gas mixture can be used without cleansing. But even relatively pure methane is easy to obtain. Hydrogen sulfide can be removed from biogas by passing it over iron filings. Carbon dioxide can be scrubbed out with lime water (calcium hydroxide). Water vapor can be removed through absorption. The remaining gas, methane, has a high energy content.

Biogas plants have few detractors, but some of their proponents fear that things are moving too fast and that large sums of money may be invested in inferior facilities when significant improvements may wait just around the corner. A recent report to the Economic Social Commission for Asia and the Pacific said of the Indian biogas program that "the cost should be drastically reduced, the digester temperature controlled during the winter months through the use of solar energy and the greenhouse effect, and the quality of the effluent improved," before huge amounts of scarce capital are sunk in biogas technology. To these misgivings must be added those of many in the Third World who are afraid that the benefits of biogas plants may fall exclusively or primarily to those who own cattle and land—accentuating the gap between property-owners and the true rural poor.[75]

To quell the fears of those with reservations about biogas development, most government programs stress community plants and cooperative facilities; and many countries are holding off on major commitments of resources to the current generation of digesters. But, whether small or large, sophisticated or crude, fully automated or labor-intensive, privately-owned or public, biogas plants appear destined for an increasingly important role in the years ahead.

While hundreds of thousands of successful anaerobic digesters are already in operation, many other energy conversion technologies are also attracting increased interest. Hydrolysis, for example, can be used to obtain ethanol from plants and wastes with a high cellulose content at an apparent overall conversion efficiency of about 25 percent. The cellulose is hydrolyzed into sugars, using either enzymes or chemicals; the sugar, in turn, is fermented by yeast into ethanol. Though most research on hydrolysis has thus far been small in scale, Australians have advanced proposals for producing prodigious quantities of ethanol using eucalyptus wood as the base and concentrated hydrochloric acid as the hydrolyzing agent. Ethanol so produced could substitute for a large share of Australia's rising oil imports.[76]

Pyrolysis is the destructive distillation of organic matter in the absence of oxygen. At temperatures above 500°C, pyrolysis requires only atmospheric pressure to produce a mixture of gases, light oil, and a flaky char—the proportions of each being a function of operating conditions. In particular, this process recommends itself for use with woody biomass that cannot be digested anaerobically.

True pyrolysis is endothermic, requiring an external heat source. Many systems loosely termed "pyrolysis" are actually hybrids, employing combustion at some stage to produce heat. Three of the dozen or so systems now under development are far enough along to warrant comment. The Garrett "Flash Pyrolysis" process involves no combustion, but its end product (a corrosive and highly viscous oil) has a low energy content. The Monsanto "Langard" gas-pyrolysis process can be used to produce steam with an overall efficiency of 54 percent. The Union Carbide "Purox" system, a high-temperature operation with a claimed efficiency of 64 percent, uses pure oxygen in its combustion stage and produces a low-Btu gas.[77]

Hydrogasification, a process in which a carbon source is treated with hydrogen to produce a high-Btu gas, has been well studied for use with coal. But further research is needed on its potential use with biomass since, for example, the high moisture content of biomass may alter the reaction. Similarly, fluidized-bed techniques, which work well with coal, may require a more uniform size, shape, density, and chemical composition than biomass often provides. Experimental work on the application of fluidized-bed technologies to biomass fuels is now being conducted by the U.S. Bureau of Mines in Brucetown, Pennsylvania.

"The selection of energy systems will be partially dictated by the type of fuel desired: the ends will specify the means."

Hydrogenation, the chemical reduction of organic matter with carbon monoxide and steam to produce a heavy oil, requires pressures greater than 100 atmospheres. The U.S. Energy Research and Development Administration is paying for a $3.7-million pilot plant at Albany, Oregon; at the Albany plant, hydrogenation will be used to tap the energy in wood wastes, urban refuse, and agricultural residues.

The selection of energy systems will be partially dictated by the type of fuel desired: the ends will specify the means. In a sense, the development of biological energy sources is a conservative strategy, since the products resemble the fossil fuels that currently comprise most of the world's commercial energy use. Some fuels derived from green plants could be pumped through existing natural gas pipelines, and others could power existing automobiles. Nuclear power, in contrast, produces only electricity, and converting to an energy system that is mostly electric would entail major cultural changes and enormous capital expenditures.

Biomass processes can be designed to produce solids (wood and charcoal), liquids (oils and alcohols), gases (methane and hydrogen), or electricity. Charcoal, made through the destructive distillation of wood, has been used for at least 10,000 years. It has a higher energy content per unit of weight than does wood; its combustion temperature is higher, and it burns more slowly. However, four tons of wood are required to produce one ton of charcoal, and this charcoal has the energy content of only two tons of wood. For many purposes—including firing boilers for electrical generation—the direct use of wood is preferable. Charcoal, on the other hand, is better suited to some specialized applications, such as steel-making.

Methanol and ethanol are particularly useful biomass fuels. They are octane-rich, and they can be easily mixed with gasoline and used in existing internal combustion engines. Both were commonly blended with gasoline, at up to 15 to 25 percent, respectively, in Europe between 1930 and 1950. Brazil recently embarked upon a $500-million program to dilute all gasoline by 20 percent with ethanol made from sugar cane and cassava. Meanwhile, several major U.S. corporations are showing keen interest in methanol. These alcohols could also fuel low-polluting external combustion engines.[78]

The gaseous fuels produced from biomass can be burned directly to cook food or to provide industrial process heat. They can also be used to power pumps or generate electricity. Moreover, high quality gases such as methane or hydrogen can be economically moved long distances via pipeline. A "synthesis gas" consisting of hydrogen and carbon monoxide was manufactured from coke in most U.S. towns at the turn of the century; known popularly as "town gas," it was piped to homes for lighting and cooking. A similar "local brew" might make sense today for areas rich in trees but poor in the type of biomass needed for anaerobic digestion. Synthesis gas can be further processed into methane, methanol, ammonia, or even gasoline.

The price in constant dollars for oil-based fuels declined during the 1950s and 1960s, partly because uses were found for more and more of the by-products of the refining process. Similarly, as the residues of biological energy processes find users, the production of fuels from biomass will grow more economically attractive.

Many biomass schemes reflect the assumption that energy crops can supply food as well as fuel. Even the plans to cultivate islands of deep-sea kelp include schemes for harvesting abalone in the kelp beds. Many energy crops, including water hyacinths, have proven palatable to cattle and other animals, once solar dryers have reduced moisture to appropriate levels.

More sophisticated by-product development has also been planned by students of chemurgy, the branch of applied chemistry concerned with the industrial use of organic raw materials. In the 1930s, George Washington Carver produced a multitude of industrial products from peanuts, while Percy Julian derived new chemicals from vegetable oils. And, for the record, the plastic trim on the 1936 Ford V-8 was made from soybeans.

Organic fuels can bear many different relationships to other products. Sometimes the fuels themselves are the by-products of efforts to produce food (e.g., sugar), natural fibers (e.g., paper), and lumber or wood chemicals (e.g., turpentine). Sometimes the residues of fuel-producing processes may be turned into plastics, synthetic fibers, detergents, lubricating oils, greases, and various chemicals.

Biological energy systems are free of the more frightening drawbacks associated with current energy sources. They will produce no bomb-grade materials nor radioactive wastes. In equilibrium, biological energy sources will contribute no more carbon dioxide to the atmosphere than they will remove through photosynthesis; and switching to biomass conversion will reduce the cost of air pollution control since the raw materials contain less sulfur and ash than many other fuels do. Indeed, some biological energy systems would have positive environmental impacts. Reforestation projects will control soil erosion, retard siltation of dams, and improve air quality. One type of biomass, water hyacinths, can control certain forms of water pollution, while others remove many air pollutants.

Without wise management, however, biological energy systems could engender major environmental menaces. The most elementary danger associated with biomass production is robbing the soil of its essential nutrients. If critical chemicals in the soil are not recycled, this "renewable" energy resource will produce barren wastelands.

Recycling nutrients can, alas, bring its own problems. First, if industrial wastes are included in the recycled material, toxic residues may build up in the soil. Some evidence suggests that certain contaminants—especially such heavy metals as cadmium and mercury—are taken up by some crops. Second, some disease-causing agents, especially viruses, may survive sewage treatment processes. Many of these potential infectants found in wastes can be controlled simply by aging the sludge before returning it to the soil. But, during outbreaks of particularly virulent diseases, human excrement will have to be treated by other means, such as pasteurization, before being applied to agricultural lands.

Because of the relatively low efficiency with which plants capture sunlight, huge surfaces will be needed to grow large amounts of biomass. If biological energy farms significantly alter existing patterns of surface vegetation, the reflectivity and the water-absorption patterns of immense tracts of land could change. Moreover, new demands for gigantic tracts of land may eventually intrude upon public reserves, wetlands, and wilderness areas.

Ocean farming can go overboard too. The surface of the deep ocean is largely barren of plant nutrients, and large-scale kelp farming of the deep ocean might involve the use of wave-driven pumps to pull cold, nutrient-rich water from the depths up to the surface. A 100,000-acre farm might require the upwelling of as much as two billion tons of water a day, with unknown consequences for the marine environment. Deep waters also contain more inorganic carbon than surface waters do; upwelling such waters would entail the release of carbon dioxide into the atmosphere. (Ironically, a classic defense of biological energy systems has been that they would avoid the build-up of atmospheric CO^2 associated with the combustion of fossil fuels.) All these effects might be somewhat mitigated if ocean farms were located in cooler regions to the north and south, where the temperature difference between surface waters and deep waters is less.

If the quest for energy leads to the planting of genetically similar crops, the resulting monocultures will suffer from the threats that now plague high-yielding food grains. Vulnerability to pests could necessitate widespread application of long-lived pesticides. An eternal evolutionary race would begin between plant breeders and blights, rots, and fungi. Moreover, biological energy systems are themselves vulnerable to external environmental impacts. A global cooling trend, for example, could significantly alter the growing season and the net amount of biomass an area could produce.

Using biomass conversion requires caution and respect for the unknown. If the expanded use of biological energy sources in equatorial countries resulted in the spread of harvesting technologies designed for use in temperate zones, dire effects could follow. If the biomass fuels became items of world trade instead of instruments of energy independence, the sacking of Third World forests by multinational lumber and paper companies could be accelerated.

"**The broad social effects of biological energy systems defy pat predictions.**"

The broad social effects of biological energy systems defy pat predictions. Biological energy systems could, for example, be designed to be labor-intensive and highly decentralized, but there is no guarantee that they will evolve this way of their own accord. Like all innovations, they must be carefully monitored; like all resources, they must be used to promote equity and not the narrow interests of the elite.

Photosynthetic fuels can contribute significantly to the world's commercial energy supply. Some of these solid, liquid, and gaseous fuels are rich in energy; and most can be easily stored and transported. Plant power can, without question, provide a large source of safe, low-polluting, relatively inexpensive energy. But all energy systems have certain intractable limits. For photosynthetic systems, these include the availability of sunlight and the narrowness of the radiation range within which photosynthesis can occur. Access to land, water, and nutrients will also set production boundaries. And, at a more profound level, we must ask how much of the total energy that drives the biosphere can be safely diverted to the support of a single species, *Homo sapiens*.

Storing Sunlight

Jets and trucks cannot run directly on sunbeams. At night, of course, nothing can. Solar energy is too diffuse, intermittent, and seasonally variable to harness directly to serve some human needs. Of course, interruptions of various kinds plague all energy systems, and storage problems are not unique to renewable power sources. Electrical power lines snap, gas and oil pipelines crack, dams run low during droughts, and nuclear power plants frequently need repairs and maintenance. A wind turbine on a good site with sufficient storage capacity to handle a 10-hour lull could, Danish physicist Bent Sørensen has shown, deliver power as reliably as a typical modern nuclear power plant. Reliability is thus a relative concept.[79]

Sometimes the intermittent nature of an energy source causes no problems. For example, solar electric facilities with no storage capacity can be used to meet peak demands, since virtually all areas have their peak electrical demands during daylight hours. Some users, such as fertilizer producers, may find that an intermittent energy source satisfies their needs. And sometimes two intermittent sources will complement each other. For example, wind speeds are usually highest when the sun is not shining, so wind and solar devices can often be effectively used in tandem.

Often, however, energy must be stored. One option is to store energy as heat. Low-temperature heat for warming buildings, for example, can be temporarily stored in such substances as water or gravel; in fact, substantial short-term heat storage capacity can be economically designed into the structural mass of new buildings. For longer periods, eutectic (phase-changing) salts are a compact, effective storage medium. Higher-temperature heat, suitable for generating electricity, can be stored in hot oil or perhaps in molten sodium. A 1976 report for the U.S. Electric Power Research Institute rated thermal storage (along with pumped hydro-storage and compressed air storage) as one of the most promising options for central utilities.[80]

Many solar enthusiasts are intrigued by hydrogen storage systems. The distinguished British scientist and writer J. B. S. Haldane predicted in a lecture given at Cambridge University in 1923 that England would eventually turn for energy to "rows of metallic windmills working electric motors." Haldane then went on:

> At suitable distances, there will be great power stations where during windy weather the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen. These gases will be liquefied and stored in vast vacuum jacketed reservoirs, probably sunk in the ground . . . . In times of calm, the gases will be recombined in explosion motors working dynamos which produce electrical energy once more, or more probably in oxidation cells.[81]

Little has been done to advance large-scale hydrogen usage since Haldane startled Cambridge with his vision more than a half century ago. The reason for the lapse is easy enough to fathom; fossil fuels were for decades so cheap that hydrogen could not be made competitive. In recent years, interest in hydrogen has revived, partly because this fuel has been used so successfully in space exploration programs and partly because natural gas companies have gradually begun to awaken from their "pipe dreams" of endless natural gas supplies.

Under some grand schemes, hydrogen would someday substitute for all natural gas, replace all automobile fuel, and satisfy much of industry's total energy demand as well. But the most far-fetched of such plans for a "hydrogen economy" strain the imagination. The easiest way to make hydrogen (other than by re-forming fossil hydrocarbons) is by electrolyzing water; the United States would have to triple its present electrical generating capacity in order to substitute hydrogen for the natural gas it now uses—even if it were to devote *all* its electricity to the task.

Hydrogen production poses a technical problem but it is one that may eventually yield to a cheap technical solution. In fact, some promising research is now being conducted on biological production processes and on techniques for using high-temperature solar heat to split water molecules into hydrogen and oxygen. In the meantime, hydrogen recommends itself for use in storing and transporting energy from intermittent sources of power. Easily stored as a pressurized gas, as a super-cooled liquid, or in metal hydrides, hydrogen can also be transported long distances more economically than electricity and can be used in fuel cells (where it can be efficiently converted into electricity in decentralized facilities). Pressurized hydrogen tends to embrittle some metals and alloys, but the importance of this problem has probably been exaggerated.[82]

Pumped hydro-storage involves using surplus power to pump water from a lower reservoir to an elevated one. Then, when power is needed, the water is allowed to flow back to the lower pool through a turbine. Pumped hydro-storage is already used with conventional power plants around the world; in the future it may be crossbred with wind-power technologies. The use of wind energy declined in Denmark a half century ago in part because "wind muscle" could not compete economically with cheap, surplus Swedish hydropower. Now that demand for electricity has increased in both countries, both are seriously considering investing in a hybrid system. Danish wind power could replace some Swedish hydropower when the wind blows, and any surplus wind power could be used to pump downstream water back into some of Sweden's reservoirs. Sweden might also pursue wind power independently. The Swedish State Power Board has determined that 5,000 megawatts of wind-power capacity could be linked with current hydro-electric facilities without providing extra storage. Such a combination of wind power and hydropower would make sense in many places: when a dam has excess capacity and could generate more electricity without adding more turbines if only it held more water, a hybrid system fits the bill. The Bonneville Power Administration is considering the integration of wind turbines into its extensive hydro-electric system in the northwestern United States.

Another form of mechanical storage involves pumping pressurized air into natural reservoirs (e.g., depleted oil and gas fields), man-made caverns (including abandoned mines), or smaller specially-made storage tanks. Air stored in this manner is released as needed to drive turbines or to run machinery. For almost four decades, designers have studied large-scale pumped-air storage proposals, but the first commercial unit is just being completed. Located in Huntorf, West Germany, the system will store the surplus power generated by nuclear reactors during periods of low power-demand.[83]

Still another approach to mechanical storage involves rapidly rotating flywheels in environments that are almost friction-free. Recent major advances in materials now allow the construction of "superflywheels" whose higher spinning speeds enable them to store large amounts of energy in rather small areas. Flywheels could, in theory, be made small and efficient enough to propel individual automobiles. They have already been used in pilot projects on trolleys and buses to recapture the energy that would otherwise be lost during braking. Although superflywheels seem attractive at first blush, significant problems remain; and these devices are some years away from widespread commercial application.[84]

Electricity can be stored directly in batteries. Existing batteries are rather expensive, have low power and energy densities, and do not

"Overall, the storage requirements for a society based on renewable energy sources may prove comparable to those of an all-nuclear society."

last long. However, experimental batteries, some of which may prove economical and feasible when used with intermittent energy sources, may soon enter the market. Metal-gas batteries, like the zinc-chloride cell, use inexpensive materials and have relatively high energy densities. Alkali-metal batteries perform very well, but operate at high temperatures, and existing models suffer from short life spans. A number of other battery possibilities are being investigated and some promising preliminary research results are now emerging.[85]

Base-load sources of electricity, such as coal plants and nuclear plants, also require storage. Such facilities cannot be geared up and down to follow the peaks and valleys of electrical usage; they produce power at a steady rate, and surplus power from non-peak hours must be stored for the periods of heaviest demand. For base-load plants, the cost of storage varies with the degree to which consumer usage is not constant 24 hours a day. For solar sources, the storage costs vary with the extent to which usage does not coincide with the normal daytime sunlight cycle. Wind power is less predictable, but at choice sites tends to be quite constant. Storage problems with hydropower and biomass systems are minimal. Overall, the storage requirements for a society based on renewable energy sources may prove comparable to those of an all-nuclear society.

Storage ranks high among the uncertainties that impede the use of long-term energy sources. Although studies have been performed, none has yet established which storage systems will have an economic edge. It is clear, however, that storage devices should be carefully keyed to the actual quality of energy needed for a particular end-use, and that electricity should never be produced and stored for a job requiring only low-grade heat. In storage as in energy production itself, thermodynamics will be crucial.

Turning Toward the Sun

We are *not* running out of energy. But we *are* running out of cheap oil and gas. We are running out of money to pay for doubling and redoubling an already vast energy supply system. We are running out of political willingness to accept the social costs of continued rapid energy expansion. We are running out of the environmental capacity needed to handle the pollutants generated in conventional energy production. And we are running out of time to adjust to these new realities.

Humankind is no closer today than it was two decades ago to finding a replacement for oil, and the rhetoric that public officials lavish upon the energy "crisis" is still not being translated into action. Most energy policy continues to be framed as though it were addressing a problem that our grandchildren will inherit. But the energy crisis is *our* crisis. Oil and natural gas are our principal means of bridging today with tomorrow, and we are burning our bridges.

The energy crisis demands rapid decisions, but policies must nevertheless be formulated with an eye to their wide-reaching implications. The world will not undergo a major energy transition without also undergoing fundamental social and political changes. The changes some energy alternatives dictate may be preferable to others, but some form of fundamental change is inevitable.[86]

If small-scale, decentralized renewable-energy technologies were embraced, few aspects of modern life would go unaffected. Farms would begin to rely on wind power, solar heaters, and waste conversion technologies to supply a large fraction of their energy needs. Food storage and preparation would similarly grow dependent upon solar-powered technologies. Gradually, meat consumption in the industrial world would drop, and the food-processing industry would become more energy-efficient and less pervasive in its impact on diets.

In the new energy era, transportation would be weaned from its petroleum base even as improved communications and intelligent city planning began to eliminate pointless travel. Energy efficiency and load factors would become important criteria in evaluating transport modes, and the costs of travel would reflect these values. Bicycles would begin to account for an important fraction of commuter traffic, as well as of other short trips. And freight would be transferred wherever possible from trucks and planes onto more efficient modes, especially trains and ships.

If we were to opt for the best renewable-energy technologies, buildings could be engineered to take full advantage of their environments. More and more of the energy needed for heating and cooling would be derived directly from the sun. Using low-cost photovoltaics that convert sunlight directly into electricity, many buildings could eventually become energy self-sufficient. New jobs and professions would develop around the effort to exploit sunlight, and courts would be forced to consider the "right" of building owners not to have their sunshine blocked by neighboring structures.

While industry would doubtless turn to coal for much of its energy during the transition period, eventually it would also draw its primary energy from natural flows. Thus, energy availability would play an important role in determining the locations of future factories. The sunshine-rich nations of the Third World, where raw materials and renewable energy sources are most plentiful, could become new centers of economic productivity. The across-the-board substitution of cheap fuel for human labor would be halted. Recycled metals, fibers, and other materials would become principal sources of raw materials. Seen as energy repositories, manufactured products would necessarily become more durable and would be designed to be easily repaired and recycled.

Using small, decentralized, and safe technologies makes sense from a systems-management point of view. Small units could be added incrementally if rising demands required them, and they would be much easier than large new facilities to integrate smoothly into an energy system. Small, simple sources could be installed in a matter of weeks or months; large, complex facilities often require years and even decades to erect. If gigantic power plants were displaced by thousands of smaller units dispersed near the points of end-use, economies of size would become relatively less important vis-á-vis economies of mass production. Technology would again concern itself with simplicity and elegance, and vast systems with elaborate control mechanisms would become extinct as more appropriately scaled facilities evolved.[87]

To decentralize power sources is in a sense to act upon the principle of "safety in numbers." When large amounts of power are produced at individual facilities or clusters of plants, the continued operation of these plants becomes crucial to society. Where energy production is centralized, those seeking to coerce or simply to disrupt the community can easily acquire considerable leverage: for example, a leader of the British electrical workers recently noted that "the miners brought the country to its knees in eight weeks," but that his coworkers "could do it in eight minutes." Disruption need not be intentional either. Human error or natural phenomena can easily upset fragile energy networks that serve wide areas, while use of diverse decentralized sources could practically eliminate such problems.

However, research on direct and indirect solar sources will not automatically produce devices that meet the diverse needs of the world's peoples. Every technology embodies the values and conditions of the society it was designed to serve. Most significant research on sustainable energy sources has been carried out in industrialized countries; technological advances have therefore reflected the needs of societies with temperate climates, high per capita incomes, abundant material resources, sophisticated technical infrastructures, expensive labor, good communication and transportation systems, and well-trained maintenance personnel. Such societies are wired for electricity—indeed, two-thirds of the U.S. solar energy research budget is devoted to the generation of electricity.[88]

Clearly, some of the findings of research conducted in such nations are not easily or wisely transferred to societies with tropical climates, low per capita incomes, few material resources, stunted technical infrastructures, cheap labor, poor communications, and only fledgling maintenance forces. Most people in the world do not have electrical outlets or anything to plug into them. What they need are cheap solar cookers, inexpensive irrigation pumps, simple crop dryers, small solar furnaces to fire bricks, and other basic tools.

With the traps of technology transfer in mind, some argue that a major solar research and development effort on the part of the industrialized world cannot speak to the true needs of the poorer countries. This argument contains a kernel of truth in a husk of misunderstanding. Countries can choose to learn from each other's

"Most people in the world do not have electrical outlets or anything to plug into them."

experience; but each country must view borrowed knowledge through the lens of its own unique culture, resources, geography, and institutions. The differences between such industrialized lands as Japan and France merit note, but the differences between some Third World countries may be more striking than the similarities. Surinam (with an annual per capita income of $810) has energy problems and potential solutions that bear little resemblance to those of Rwanda (with an annual per capita income of about $60). And national wealth is not the only relevant difference. The tasks for which energy is needed vary from country to country. In some, the most pressing need may be for energy to run the pumps that bring water from a deep water table to the parched surface. In lands with more abundant water supplies, cooking fuel may be in desperately short supply. The availability of sustainable resources may also differ. One region may have ample hydropower potential, another strong winds, and a third profuse direct sunlight. Successful technology transfers require a keen sensitivity to such differences.

Some disillusioned solar researchers in both industrialized and agrarian countries contend that the major impediment to solar development has been neither technical (the devices work) nor economic (many simple devices can be cheaply made). Instead, they claim, the problems have social and cultural roots. Many Third World leaders have not wanted to settle for "second-rate" renewable energy resources while the industrial world flourished on oil and nuclear power. Often, officials in charge of new technologies, such as windmills, have been unable to find technicians who could maintain and repair the systems. Occasionally, people given solar equipment have refused to use it because the rigid time requirements of solar technology disrupted their daily routines or because the direct use of sunlight defied their cultural traditions.

Many of these attitudinal impediments may now be vanishing as the global South begins to develop its own research and development capacity. The indigenous technologies born of this new capability may prove quite compatible with Third World needs. Brazil's large ethanol program, India's gobar gas plants, and the Middle East's growing fascination with solar electric technologies can all bode well for the future of renewable energy resources. At the same time, the people of the Third World, stunned by a simultaneous shortage of firewood and petroleum, may be more willing than they were a few years ago to adopt solar solutions.

In much of the global North as well, solar technologies are being embraced as important future options. In Japan, the Soviet Union, France, and the United States, renewable resources are increasingly being viewed as major components of future energy planning. Some of the innovative research in these countries could well hold global significance.

The attractions of sunlight, wind, running water, and green plants as energy sources are self-evident. Had industrial civilization been built upon such forms of energy "income" instead of on the energy stored in fossil fuels, any proposal to convert to coal or uranium for the world's future energy would doubtless be viewed with incredulous horror. The current prospect, however, is the reverse—a shift from trouble-ridden sources to more attractive ones. Of the possible worlds we might choose to build, a solar-powered one appears most inviting.

Notes

1. By far the largest fraction of current commercial solar usage is of biomass. In many Third World countries, firewood, dung, and crop residues constitute 90 percent of all energy use. Calculations regarding the magnitude of this usage can be found in Arjun Makhijani and Alan Poole, *Energy and Agriculture in the Third World* (Cambridge, Mass.: Ballinger, 1975), and D.F. Earl, *Forest Energy and Economic Development* (Oxford: Clarendon Press, 1975). Hydropower ranks next, providing more than one-fifth of all electricity and about 3 percent of all end-use energy. See United Nations, *World Energy Supplies: 1950-1974* (New York: Department of Economic and Social Affairs, 1976).

2. F. de Winter and J.W. de Winter, eds., *Description of the Solar Energy R&D Programs in Many Nations* (Santa Clara, California: Atlas Corporation, February 1976).

3. I am indebted to Professor Theodore Taylor of Princeton University for suggesting this analysis. More information on the CO_2 problem can be obtained in Stephen H. Schneider, *The Genesis Strategy: Climate and Global Survival* (New York: Plenum Press, 1976); Bert Bolin, *Energy and Climate,* (Stockholm: Secretariate for Future Studies, 1975); W.S. Broeker, "Climate Change: Are We on the Brink of a Pronounced Global Warming?" *Science,* August 8, 1975; P.E. Damon and S.M. Kunen, "Global Cooling?" *Science,* August 6, 1976. The problems associated with a plutonium economy are elaborated in Denis Hayes – *Nuclear Power: The Fifth Horseman* (Washington, D.C.: Worldwatch Institute, 1976).

4. An overview of the major components of the U.S. fusion program can be obtained from the Energy Research and Development Administration, *Fusion Power by Magnetic Confinement Program Plan,* Volumes I, II, III, and IV (Washington, D.C.: July 1976). For an excellent survey of the technical problems faced by fusion written from an optomistic viewpoint, see David J. Rose and Michael Feirtag, "The Prospect for Fusion," *Technology Review,* December 1976. For a more skeptical appraisal, see the three-part series by William Metz, "Fusion Power: What is the Program Buying the Country?" *Science,* June 25, 1976; "Fusion Research: Detailed Reactor Studies Identify More Problems," *Science,* July 2, 1976; "Fusion Research: New Interest in Fusion-Assisted Breeders," *Science,* July 23, 1976.

5. Comprehensive overviews of solar energy can be found in Farrington Daniels, *Direct Use of the Sun's Energy* (New York: Ballantine Books, 1974) and B.J. Brinkworth, *Solar Energy for Man* (New York: John Wiley and Sons, 1972). Two more recent articles in *Technology Review* provide excellent analyses of the solar potential: Walter E. Morrow, Jr., "Solar Energy: Its Time is Near," December 1973, and John B. Goodenough, "The Options for Using the Sun," October-November 1976. The most exhaustive survey of all renewable energy technologies remains Wilson Clark, *Energy for Survival* (Garden City, New York: Anchor Press/Doubleday, 1974). A recent survey of U.S. corporate interest in several of these technologies is Stewart W. Herman and James S. Cannon, *Energy Futures* (New York: Inform, Inc., 1976).

6. Insight into the many vital but unnoticed functions performed for humankind by the sun can be gleaned from Frank Von Hippel and Robert H. Williams, "Solar Technologies," *Bulletin of the Atomic Scientists*, November 1975, and Steve Baer, "Clothesline Paradox," *The Elements*, November 1975. The temperature estimate for a sunless earth was provided in Vincent E. McKelvey, "Solar Energy in Earth Processes," *Technology Review*, April 1975.

7. John V. Krutilla and R. Talbot Page, "Energy Policy from an Environmental Perspective," in Robert J. Kalter and William A. Vogely, eds., *Energy Supply and Government Policy* (Ithaca, N.Y.: Cornell University Press, 1976); John S. Reuyl, *et al., A Preliminary Social and Environmental Assessment of the ERDA Solar Energy Program 1975-2020*, Vols. I and II (Menlo Park, California: The Stanford Research Institute, 1976) found solar technologies to be environmentally attractive compared to the alternatives.

8. Hans H. Landsberg, "Low-Cost Abundant Energy: Paradise Lost?" (Washington, D.C.: Resources for the Future Reprint Number 112, December 1973).

9. The U.S. Federal Energy Administration publishes a semi-annual *Survey of Solar Collector Manufacturing Activity;* the 1977 estimate is by Ronald Peterson, Director of Grummon Energy Systems, one of the largest manufacturers of solar collectors.

10. Largely because conventional fuels pose transportation and distribution problems, the largest immediate market for expensive photovoltaic cells may, strangely enough, be in the world's poorest countries. Charles Weiss and Simon Pak, "Developing Country Applications of Photovoltaic Cells," presented to the ERDA National Solar Photovoltaic Program Review Meeting, San Diego, California, January 20, 1976.

11. M.L. Baughman and D.J. Bottaro, *Electric Power Transmission and Distribution Systems: Costs and Their Allocation* (Austin: University of Texas Center for Energy Studies, July 1975).

12. An excellent exploration of the concept of thermodynamic matching is in "Efficient Use of Energy: A Physics Perspective," The American Physical Society, January 1975. (Reprinted in U.S. House of Representatives, Committee on Science and Technology, Part I, ERDA Authorization Hearings, February 18, 1975). Simpler explanations can be found in Barry Commoner, *The Poverty of Power* (New York: Alfred A. Knopf, 1976), and Denis Hayes, *Energy: The Case for Conservation* (Washington, D.C.: Worldwatch Institute, January 1976).

13. Amory B. Lovins, "Scale, Centralization, and Electrification in Energy Systems," presented to a Symposium on Future Strategies of Energy Development, Oak Ridge, Tennessee, October 20-21, 1976. The Canadian data is in "Exploring Energy-Efficient Futures for Canada," *Conserver Society Notes,* May-June 1976.

14. These issues are thoughtfully explored in John S. Reuyl, *et al., A Preliminary Social and Environmental Assessment of the ERDA Solar Energy Program 1975-2020;* Amory B. Lovins, "Energy Strategy: The Road Not Taken?" *Foreign Affairs,* October 1976; and less directly by Rufus E. Miles, Jr., *Awakening from the American Dream: The Social and Political Limits to Growth* (New York: Universe Books, 1976); Bruce Hannon, "Energy, Land, and Equity," presented to the 41st North American Wildlife Conference, Washington, D.C., March 21-25, 1976; and William Ophuls, *Ecology and the Politics of Scarcity* (San Francisco: W.H. Freeman and Co., 1977).

15. Among their other virtues, flat plate collectors have a high net energy yield. A conventional collector will deliver enough energy in less than one year to pay back the energy used in its manufacture. Moreover, if collectors are recycled, the energy requirements are reduced dramatically. See the various statements on net energy in *Solar News and Views* (International Solar Energy Society, American Section, Richmond, California) January and April 1976.

16. John A. Duffie and William A. Beckman, "Solar Heating and Cooling," *Science*, Vol. 191, No. 4223, January 16, 1976. A fine photographic survey of several U.S. solar homes can be found in Norma Skurka and Jon Naar, *Design for a Limited Planet* (New York: Ballantine Books, 1976). A more comprehensive survey is W.A. Shurcliff, *Solar Heated Buildings: A Brief Survey*, 13th edition (San Diego: Solar Energy Digest, 1977). Active approaches to solar heating are described in W.A. Shurcliff, "Active-Type Solar Heating Systems for Houses: A Technology in Ferment," *Bulletin of the Atomic Scientists*, February 1976. Passive solar design is explained in Raymond W. Bliss, "Why Not Just Build the House Right in the First Place?" *Bulletin of the Atomic Scientists*, March 1976, and by Bruce Anderson, "Low Impact Solutions," *Solar Age*, September 1976.

17. M. Telkes, "Thermal Storage in Sodium Thiosulfate Pentahydrate," presented to Intersociety Energy Commission Engineering Conference, University of Delaware, August 18, 1975.

18. H.C. Fischer, ed., *Summary of the Annual Cycle Energy System Workshop I* (Oak Ridge, Tennessee: Oak Ridge National Laboratory, July 1976).

19. Complete information on and specifications for this air conditioning system are available from the Yazaki Buhin Company, Ltd., 390, Umeda Kosai City, Shizuoka Prefecture, Japan.

20. The Mitre Corporation, *An Economic Analysis of Solar Water and Space Heating* (Washington, D.C.: Energy Research and Development Administration, November 1976); R.A. Tybout and G.O.G. Loff, "Solar House Heating," *Natural Resources Journal*, Vol. 10, No. 2, April 1970.

21. This is the most persuasive argument available to those who favor utility investments in solar technologies and conservation. A utility should in theory be willing to make electricity-saving investments up to the high *marginal* cost of new power plants, whereas the consumer will want to make only those investments that are sensible in light of *average* electrical bills. Arguments against such utility involvement are generally based on the assumption that the utility will charge high prices for equipment and labor while demanding an exorbitant rate-of-return on its investment. In parts of the world where utilities are government-regulated, this argument loses much of its force.

22. Frost and Sullivan, *The U.S. Solar Power Market*, Report No. 348, New York, 1975. Frost and Sullivan estimates the total annual U.S. solar market for 1985, including wind power and biomass, at $10 billion. In its *A Nation of Energy-Efficient Buildings by 1990* (Washington, D.C.: 1975), the American Institute of Architects calculates that an ambitious program of conservation and solar development could save the United States the equivalent of 12.5 million barrels of oil a day in 1990. The institutional obstacles such rapid solar development would have to overcome are discussed in R. Schoen, A.S. Hirshberg, and J. Weingart, *New Energy Technology for Buildings* (Cambridge, Mass.: Ballinger, 1975).

23. Multiple-effect solar stills are described in "Solar Desalting Process Breakthroughs," *Solar Energy Digest*, June 1976.

24. "French Solar-Powered Irrigation Pump Installed in Mexico," *Solar Energy Digest*, February 1976.

25. D. Procter and R.F. White, "The Application of Solar Energy in the Food Processing Industry," presented to a meeting of the Australian and New Zealand Sections of I.S.E.S., Melbourne, Australia, July 2, 1975.

26. Malcolm Fraser, *Analysis of the Economic Potential of Solar Thermal Energy to Provide Industrial Process Heat* (Warrenton, Virginia: Intertechnology Corporation, 1977). A concentrating solar collector can quite easily obtain a temperature of 288°C.

27. The energy demand projections used by the U.S. Energy Research and Development Administration to justify a massive nuclear power program were carefully analyzed by Frank von Hippel and Robert Williams, "Energy Waste and Nuclear Power Growth," *Bulletin of the Atomic Scientists*, December 1976. The authors found that the projections demanded the use of electricity for virtually everything. The most egregious example of electrical "padding" was for industrial process heat. Virtually no electricity is used this way today; yet the projections show the 2020 electrical demand for process heat to be larger than that for all electricity used in the entire U.S. economy in 1975. Fraser, in *Analysis of the Economic Potential*, found that half of this energy could be provided by direct solar heating; most of the remaining half can be more easily obtained from biomass or other fuels than from electricity.

28. Aden Baker Meinel and Marjorie Pettit Meinel, *Power for the People*, (Tucson, Arizona: privately published, 1970).

29. Arguments for closed-cycle OTECs can be found in U.S. House of Representatives, Subcommittee on Energy of the Committee on Science and Astronautics, *Solar Sea Thermal Power*, Hearings, May 23, 1974. Open-cycle OTECs are advocated in Earl J. Beck, "Ocean Thermal Gradient Hydraulic Power Plant," *Science*, July 25, 1975, and in Clarence Zener and John Fetkovitch, "Foam Solar Sea Power Plant," *Science*, July 25, 1975.

30. An excellent series of papers was prepared under the auspices of the American Society of International Law for the 1976 Workshop on Legal, Political, and Institutional Aspects of Ocean Thermal Energy Conversion. Of particular interest is Carlos Stern's skeptical paper, "An Economic Assessment of Ocean Thermal Energy Conversion." For a more optimistic assessment of OTEC economics, see Clarence Zener, "Solar Sea Power," *Bulletin of the Atomic Scientists*, January 1976.

31. R.H. Williams, "The Greenhouse Effect for Ocean Based Solar Energy Systems," Working Paper No. 21, Center for Environmental Studies, Princeton University, October 1975.

32. An excellent introduction to photovoltaics can be found in Bruce Chalmers, "The Photovoltaic Generation of Electricity," *Scientific American*, October 1976. For a more detailed treatment see Joseph A. Merrigan, *Sunlight to Electricity: Prospects for Solar Energy Conversion by Photovoltaics* (Cambridge, Mass.: MIT Press, 1975).

33. A recent technical survey of photovoltaic materials and techniques can be found in the 2-volume *Proceedings of the E.R.D.A. Solar Photovoltaic Program Review Meeting*, August 3-6, 1976 (Springfield, Virginia: National Technical Information Service, 1976).

34. See, for example, the testimony of Paul Rappaport and others in *Solar Photovoltaic Energy*, Subcommittee on Energy of the House Committee on Science and Astronautics, Washington, D.C., Hearings, June 6 and 11, 1974

35. A useful overview of the Japanese program is provided by Akira Uehara, "Solar Energy Research and Development in Quest for New Energy Sources," *Technocrat*, Vol. 9, No. 3. See also *Japan's Sunshine Project* (Tokyo: MITI Agency of Industrial Science and Technology, 1975).

36. The two-year payback period (for cells with an expected lifetime of more than 20 years) has become conventional wisdom among the silicon photovoltaic specialists. See, for example, Martin Wolfe, "Methods for Low-Cost Manufacture of Integrated Solar Arrays," and P.A. Iles, "Energy Economics in Solar Cell Processing," both in *Proceedings of the Symposium on the Material Science Aspects of Thin Film Systems for Solar Energy Conversion,* May 20-24, Tuscon, Arizona (Washington, D.C.: National Science Foundation, 1974). The calculations by Slesser and Hounam based upon a two-year payback are in M. Slesser and I. Hounam, "Solar Energy Breeders," *Nature,* July 22, 1976. E.L. Ralph, Vice President for Research at Spectrolab, claims that his company's cells now have a payback period of 87 days, and that the theoretical minimum would be on the order of 30 hours, according to a personal communication with Dr. Peter Glaser of Arthur D. Little.

37. Photovoltaics could, of course, also be used in highly centralized arrays in areas of high insulation. The advantages of decentralization are more social than technical. At the extreme are proposals to obtain large amounts of energy from photovoltaic cells on orbiting satellites, with the energy beamed down to Earth via microwaves. The idea was first suggested by Peter Glaser, "Power from the Sun: Its Future," *Science,* November 1968, and has more recently been popularized by Gerald K. O'Neill, "Space Colonization and Energy Supply to the Earth," *Co-Evolution Quarterly,* Fall 1975. The concept appears to have no insurmountable technical flaws, but is of dubious desirability. Simple, decentralized terrestrial uses of photovoltaics have far more to recommend them.

38. The largest of these sailing vessels captured about four megawatts of power from the wind. I am indebted to Professor Frank von Hippel of Princeton University for several of the ideas in this section.

39. Surveys of the history of wind power can be found in Volta Torrey, *Wind Catchers* (Brattleboro, Vermont: Stephen Green Press, 1976); E.W. Golding, *The Generation of Electricity by Wind Power* (New York: Philosophical Library, 1955); John Reynolds, *Windmills and Watermills* (New York: Praeger, 1970); A.T.H. Gross, *Wind Power Usage in Europe* (Springfield, Va.: National Technical Information Service, 1974).

40. Palmer C. Putnam, *Power From the Wind* (New York: Van Nostrand Co., 1948).

41. Don Hinrichsen and Patrick Cawood, "Fresh Breeze for Denmark's Windmills," *New Scientist,* June 10, 1976.

42. Herman and Cannon, *Energy Futures;* see also Marshal F. Merriam, "Wind Energy for Human Needs," *Technology Review,* January 1977.

43. Frank Eldridge, *Wind Machines* (Washington, D.C.: U.S. Government Printing Office, 1976). Another good survey of current wind technologies (and storage technologies) is J.M. Savino, ed., *Wind Energy Conversion Systems: First Workshop Proceedings* (Washington, D.C.: U.S. Government Printing Office, 1973).

44. J.A. Potworowski and B. Henry, "Harnessing the Wind," *Conserver Society Notes,* Fall 1976. The cost estimate is from R.S. Rangi, *et al.,* "Wind Power and the Vertical-Axis Wind Turbine Developed at the National Research Council," *DME/NAE Quarterly Bulletin,* No. 1974(2).

45. J.T. Yen, "Tornado-Type Wind Energy Systems: Basic Considerations," presented to the International Symposium on Wind Energy Systems, St. John's College, Cambridge, England, September 7-9, 1976.

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49. Hydropower resource estimates are clouded by uncertain data and ambiguous definitions. For example, such estimates typically measure either the maximum generating capacity that is usable 95 percent of the year or else the capacity usable under conditions of average annual flow. Although these figures can differ by as much as 300 percent, those who make hydropower assessments often fail to state which figure they are using. This paper employs the more conservative 95 percent figure and then reduces it sharply to reflect new constraints being imposed by environmental and agricultural interests, and also to reflect the futility of damming silt-laden streams that drain geologically unstable areas. The most comprehensive of the conventional hydropower resource estimates can be found in World Energy Conference, *Survey of Energy Resources* (New York: privately published for the World Energy Conference, 1974).

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81. Clark, *Energy for Survival.*

82. A comprehensive recent article by some of the foremost proponents of a "hydrogen economy" is D.P. Gregory and J.B. Parghorn, "Hydrogen Energy," in Jack M. Hollander, ed., *Annual Review of Energy;* a somewhat more skeptical appraisal is in J.K. Dawson, "Prospects for Hydrogen as an Energy Source," *Nature,* June 21, 1974. The fuel cell is a device that produces electricity directly from fuel through electrochemical reactions. Invented in 1839 by Sir William Grove, the fuel cell has been put to practical use in the space program. The United Technologies Corporation has embarked upon a $42-million research effort to develop a commercial fuel cell, and U.S. utilities have already signed options for the first 56 units produced. Vigorous research is also under way in many other countries.

Fuel cells have several major advantages over conventional technologies. They involve no combustion and hence virtually no pollutants. Sixty-percent conversion efficiencies are common, and 75-percent efficiencies have been reported. Unlike conventional power plants, fuel cells are as efficient with a partial load as with a peak load. Moreover, their modular design shortens construction lead times, since new modules can be added as needed. The use of decentralized fuel cells would also save the expense of constructing power lines from huge generating facilities, and would allow waste heat to be productively employed. Fuel cells are quiet, and they conserve water.

See R.S. Tantram, "Fuel Cells Past, Present, and Future," *Energy Policy,* Vol. 2, No. 1, March 1974.

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86. For example, some argue that storing energy from renewable sources would require people to change their lifestyles to conform to the periodicity of such sources. However, similar lifestyle adjustments will attend the switch to nuclear as well as solar substitutes for oil and gas. Storage costs will motivate users of solar energy sources to schedule their energy-using activities for daylight hours. Similarly, the cost of storing nuclear power will encourage consumers to even out their daily energy use. In neither case is the requirement absolute, but in both people will be rewarded for tailoring demands to fit supplies. The social changes a successful solar transition entails are discussed more fully in Denis Hayes, *Rays of Hope: The Transition to a Post-Petroleum World* (New York: W.W. Norton, 1977).

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88. The proportion of U.S. funding being applied to solar electrical generation will decline in fiscal year 1979. It is to be hoped that any cuts will be aimed at the centralized options rather than at photovoltaic research. There are not many research goals as attractive as an inexpensive, efficient photovoltaic cell.

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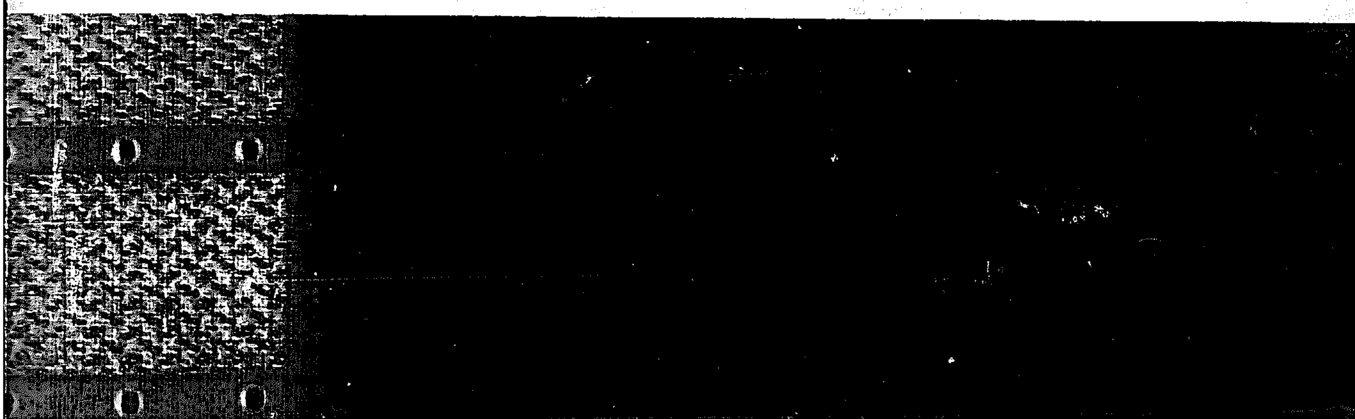

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