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ABSTRACT

This publication proposes a timetable for converting the world economy to solar energy. The contents include: (1) A solar-powered world by 2025; (2) Heating and cooling; (3) Renewable fuels; (4) Electricity; (5) Getting there from here; and (6) Notes. Numerous facts are presented within these sections. International solar research programs are reviewed briefly for Sweden, Japan, Denmark, Britain, Australia, Brazil, and China. A global energy policy is recommended. (MA)

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L. Starke
Editor

Worldwatch Institute

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The Solar Energy Timetable

Denis Hayes

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If the transition to a solar-powered world is to be completed within 50 years, major resource commitments must be made immediately Such a goal can be achieved only if an ambitious timetable of interim goals is met. Failure to begin building the equipment, establishing the infrastructure, and educating people in the skills needed in a solar era will only increase the cost and disruption of the transition and decrease the likelihood of its completion within five decades.

Meeting five-sixths of the anticipated world energy budget in the year 2025 with solar technologies could involve using more than 70 billion square meters of solar collectors and 7.5 million megawatts of solar cells World hydroelectric capacity would be quadrupled, five million wind turbines would be constructed, and about 15 percent of the world's forests would be devoted to raising wood as an "energy crop" Commitments of this magnitude are certainly possible over a 50-year period, but they are unquestionably ambitious.

A substantial body of literature has documented the technical feasibility and social desirability of solar energy sources More jobs—and less environmental deterioration—would be created per unit of energy than with any other source. The security of energy supply would be enhanced. Individuals, neighborhoods, regions, and nations would become increasingly self-reliant. And the new energy system would be sustainable for as long as the earth remains inhabitable [1]

Despite the attractions of a solar-powered world, surprisingly little thought has been given to the sheer physical requirements of a global solar transition Considering the increasingly tight constraints under which all conventional energy resources are operating, the time has

I am indebted to my colleague Christopher Flavin for his help with the research for this paper

clearly arrived for serious thought to be given to the implications of converting the world economy to solar energy. This proposed timetable is an attempt to sketch one of several possible paths to that goal.
6 It is not a "forecast," and it is certainly not a "projection." Rather it is an attempt to describe a feasible course for a world that needs to move rapidly toward increased reliance upon renewable energy resources.[2]

Oil and natural gas, which now account for about three-fifths of the world's annual fuel consumption, will almost certainly have been reduced to subordinate roles in the global energy picture by 2025. Indeed, world oil production could begin to decline before 1990. While there remains some controversy over the exact date that world oil production will "peak", the Vice Chairman of Sun Oil Company acknowledged a widely perceived truth when he recently remarked, "We are in a business that is dying." Some new source, or combination of sources, will be required to fill the gap.[3]

For some time, planners believed that the gap would be filled mostly by energy from coal and nuclear fission. While it was recognized that problems would attend the development of both these sources, the difficulties were considered to be more manageable than the crises that could result from having too little energy. An emerging body of evidence suggests this assumption may be wrong. Some of the problems associated with the large-scale worldwide development of coal and nuclear power could dwarf the stresses that such development was intended to avoid.

The relative abundance of coal leads many energy planners to think of it as a long-term energy option—a mistake seldom made for oil and gas. Thus coal is expected to be the centerpiece of the post-petroleum energy budgets in such countries as China, Australia, and the United States. While there are many unfortunate, and often unhealthy, consequences associated with coal extraction and combustion, the most intractable long-term problem arises from the atmospheric accumulation of carbon dioxide.

Carbon dioxide is produced whenever any fossil fuel is burned, but more CO_2 is produced per unit of energy released by coal combustion than by burning either oil or gas Adding CO_2 to the air raises the earth's temperature by slowing down the escape of heat into space This CO_2 greenhouse effect was a matter of speculation as recently as five years ago, but most meteorologists now agree that it is a matter of concern. An excellent report on the dangers was issued in 1977 by the U.S National Academy of Sciences Among the consequences would be a decline in food production in "breadbasket" regions, and a shift in agriculture to less fertile areas.[4]

Although there is disagreement over just how soon major changes in the earth's climate could result from the buildup of CO_2 that has already begun, many knowledgeable observers feel dire consequences are possible before 2025 A January 1978 article in the British science journal *Nature* concluded:

> If the CO_2 greenhouse effect is magnified in high latitudes, as now seems likely, deglaciation of West Antarctica would probably be the first disastrous result of continued fossil fuel consumption A disquieting thought is that if the present highly simplified climatic models are even approximately correct, this deglaciation [and the consequent five-meter rise in sea level] may be part of the price that must be paid in order to buy enough time for industrial civilization to make the changeover from fossil fuels to other sources of energy If so, major dislocations in coastal cities, and submergence of low-lying areas such as much of Florida and the Netherlands, lie ahead[5]

Nuclear power, like coal, is beset by myriad difficulties, including the risk of catastrophic accidents (especially with breeder reactors) and the disposal of long-lived radioactive wastes These difficulties, and the public concern that they have helped to generate, have caused some former nuclear champions to become pessimistic John O'Leary, Deputy Secretary of the U S Department of Energy, remarked in February 1978 that "nuclear power, which ten years ago was the hope of all energy planners, is now a 'has-been'"[6]

The most awesome problem facing nuclear power is posed by the inextricable link between this energy source and nuclear weapons

Depending upon the level of global energy demand postulated for the year 2025, meeting just half of it with nuclear power would require the recycling of between 7 million and 20 million kilograms of some
8 fissile isotope—probably plutonium-239—every year About five kilograms of any such isotope is all that is needed to make an atom bomb

The inevitability of "normal" losses during production would allow a thief who operates within the credible margin of error to divert large amounts of bomb-grade materials without detection As of August 1977, official U S inventories showed 1,534 missing kilograms of plutonium and 2,227 absent kilograms of highly enriched uranium—enough material to make 750 atom bombs It may well be that none of this material has fallen into the hands of criminals, terrorists, or foreign governments, but the material cannot be accounted for. This uncertainty would swell to much more terrifying proportions with the creation of a huge, worldwide nuclear program.

Nuclear fusion may eventually provide significant amounts of commercial electricity, but its future is uncertain at the moment. Conceptual design studies of the fusion approaches that now receive the lion's share of international research and development funding suggest that such techniques may have little commercial applicability However, a recent survey of alternative fusion concepts by the Electric Power Research Institute found several promising avenues for research—some of which could lead to comparatively small-scale, decentralized applications Nonetheless, even this generally encouraging review was not sanguine about the rapid development and commercialization of "clean" advanced fusion cycles Controlled thermonuclear fusion has yet to produce more energy than it consumes While some advanced fusion processes would provide an attractive supplement to solar resources, their successful development cannot now be counted upon.[8]

Even as the other long-term options have begun encountering unexpected problems, extraordinary strides have been made in technologies to harness the essentially inexhaustible energy of the sun Existing solar technologies can provide energy as heat, as solid, liquid, or gaseous fuels, or as electricity The sunlight that strikes the earth daily contains 10,000 times more energy than all the conventional fuels burned that day Obviously, the solar resource base is more than adequate to meet any likely level of human energy use

Technologies to harness the energy in sunlight, wind, falling water, and biomass are referred to by several names, including appropriate, light capital, intermediate, distributed, soft, and renewable The different names often carry different nuances The term 'light capital' technologies generally refers to inexpensive devices (biogas plants, for example) that Third World villages can build of indigenous materials, 'distributed technologies generally suggest decentralization as a prime criterion, soft technologies generally indicate devices that increase the efficiency with which transitional fuels are used as well as those that harness renewable resources But all refer to an energy system reliant upon energy income from the sun, rather than one dependent upon the energy capital in fossil or fissile fuels Many countries have begun to examine carefully such solar alternatives in light of their particular geographical locations and energy needs

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 For example, a hot bathtub contains more energy than does a small storage battery, but the electricity in the battery is of a higher quality than is the heat in the tub It is very difficult to power a transistor radio with a hot bathtub, and it is generally wasteful to heat bathwater with electricity In the course of considering the use of solar technologies in various countries, it will be important to bear in mind the qualitative dimension of energy demand

Conventional wisdom holds that while solar energy has many attractive characteristics, it is too expensive today for widespread application As is so often the case with conventional wisdom, yesterday's truth has become today's misapprehension Five years ago, solar energy could not compete economically with low-priced fuels But since 1973 the cost of solar equipment has dropped steadily while the costs of all competing energy sources have skyrocketed Solar technologies can now provide energy for many purposes at no higher cost than new investments in conventional energy sources

10 There remains much room for improvement. Many solar technologies can benefit from research advances, and mass production using new materials will doubtless lead to substantial reductions in cost. Increased attention to the solar prospect may lead to breakthroughs that are not now apparent In the meantime, it is possible to begin sketching the broad outlines of a global solar strategy to provide almost all of humanity s commercial energy from renewable sources by 2025.

How much energy will be needed in the year 2025? Estimates range widely Most countries assume that their fuel requirements will continue to grow for the foreseeable future If the need for an eventual energy ceiling is admitted, the day of reckoning is always thought to lie beyond the horizon of official projections Studies of future consumption patterns do not generally include an in-depth examination of a spectrum of alternative policies Policymakers ask only, "Where do we seem to be heading?" They make no attempt to grapple with the question, "What can be?"[9]

This process of gazing into a rearview mirror and proclaiming it to be a crystal ball necessarily results in certain analytical hazards During the last 25 years, world fuel consumption tripled, oil and gas consumption quintupled, and electricity use grew almost sevenfold Clearly, such trends cannot long be sustained The Arab oil embargo of 1973-74 led to the first major global discontinuity in energy growth, others will certainly follow

In an era of major discontinuities, 50-year forecasts can have only limited value at best [illegible] is necessary to formulate a vision of where we are going in order to be able to design a strategy for getting there. Our vision of 2025 would see a 75-percent larger world population using twice as much energy annually as we now use—and using it about twice as efficiently This assumes a 50-percent increase in energy use in the industrial world and a 400-percent increase in the Third World And the energy efficiency target is a reasonable goal given an aggressive world energy conservation effort.

"Solar technologies can now provide energy for many purposes at no higher cost than new investments in conventional energy sources."

Dollar for dollar, a trillion-dollar investment in increasing the energy efficiency of the world's buildings, industries, and transportation systems would save more energy than the same expenditure on new energy facilities would produce. In the United States, for example, improving the efficiency of air conditioners would save ten times as much electricity as identical investments in new power plants would produce. In India, $10 spent on improving stove efficiency can cut a typical village family's wood consumption in half—saving $10 to $25 per year. In neither case is a loss of benefit or comfort involved. And in both cases, the energy saved is just as useful as "new" energy would be.[10] 11

Comparisons between countries and within the same country over a period of years make it clear that economic well-being is not based on increases in fuel consumption. Over the past 50 years, the amount of fuel consumed per dollar's worth of goods and services produced has fallen in most countries—despite declining real energy prices. With rising energy prices a near-certainty for the foreseeable future, this trend can be expected to accelerate dramatically. This will merely require increases in the fuel-efficiency of machinery and the improved operation and maintenance of this equipment. Moreover, an intelligent program of energy conservation can actually bolster employment.[11]

Virtually all oil-importing countries have begun to take significant strides to improve energy efficiency. The nature of the energy conservation methods employed sometimes bears no particular relationship to the ideology of the government involved. In the Soviet Union, for example, the price of gasoline was doubled in March 1978, and the marketplace was relied upon to reduce gasoline consumption. In the United States, on the contrary, all efforts to remove price controls from gasoline have been soundly defeated. Reliance is instead placed upon a federal program to regulate the fuel efficiency of new cars.

Assuming, then, a vigorous effort to increase efficiency, annual world energy use from all sources in 2025 could amount to 60×10^{16} kilojoules. (A kilojoule is slightly less than a British Thermal Unit. The proposed energy budget—600 quadrillion kilojoules—equals about 570 quadrillion BTUs.) This is approximately equal to the energy released by burning 21 billion metric tons of coal Five-sixths of this 2025 energy budget could be met by renewable energy resources if the proposed timetable is followed. (See Figure 1) Thirty-six percent of this solar energy would be used directly as heat, 44 percent as solid, liquid, and gaseous fuels (mostly of biological origin), and 20 percent as electricity (See Table 1) This is a fourfold increase in the use of electricity, representing an annual growth rate of about 3 1 percent

Existing nuclear power plants, which contributed only 0 66 percent of world energy in 1977, would have long since completed their useful lifetimes, and been replaced by solar-electric facilities. Fossil fuels would contribute about one-sixth of all energy use, mostly as backup

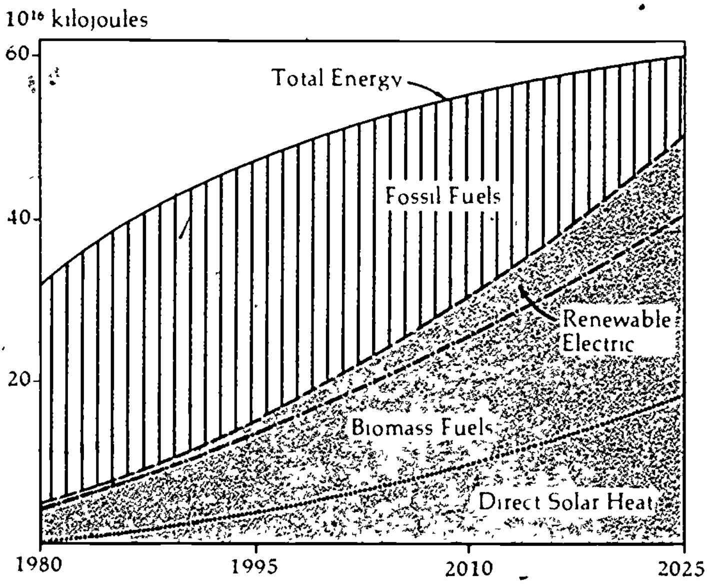

Figure 1: Proposed World Energy Production Timetable, 1980-2025*

*Energy sources supplying less than 1 percent of total are omitted for solar sources At that level of usage, these fuels would last more than 1,000 years, and the CO_2 threat would be postponed for at least two centuries—allowing succeeding generations more flexibility in the rate at which they phase out the combustion of fossil hydrocarbons

It would be possible to have a 100-percent solar energy budget by 2025 Preliminary studies have suggested how this might be accomplished in Canada, Sweden, and the United States, and it is undoubtedly feasible elsewhere The State of California, which is equivalent to the sixth largest industrial country in the world, currently has a de facto nuclear moratorium and recently began offering a 55-percent tax credit to encourage solar development. California is now the subject of the most detailed examination of solar energy prospects that has yet been undertaken, and the preliminary results suggest that a complete transition would be possible by 2025.[12]

Table 1: World Solar Energy Timetable, 1980-2025

Energy Source	1980	1995	2010	2025
		(10^{16} kilojoules)		
Active Solar Heating	0	3.0	6.0	11.0
Passive Solar Heating	0	1.0	4.0	7.0
Total Direct Solar Heat	0	4.0	10.0	18.0
Wood	4.0	6.0	7.0	8.0
Liquid Fuels	0	2.0	4.0	8.0
Gaseous Fuels	0	2.0	4.0	6.0
Total Biomass Fuels	4.0	10.0	15.0	22.0
Hydroelectric	0.5	1.0	1.5	2.0
Wind Power	0	0.5	1.0	2.0
Solar-electric	0	1.0	3.0	6.0
Total Renewable Electric	0.5	2.5	5.5	10.0
Total	4.5	16.5	30.5	50.0

Source: Worldwatch Institute

However, energy transitions have seldom led to 100 percent replacements Heavy reliance on coal began in the eighteenth century, but wood still contributes about one-sixth of the world's energy today. Heavy reliance on oil began seven decades ago, but coal still contributes more than one-fourth of the world's energy Fossil fuels, particularly oil and gas, have desirable characteristics. They have high energy densities and they are easily transported and stored. Although they are not sufficiently abundant to long sustain their current role as the world's primary sources of energy, they could and should play some role well into the twenty-first century. The world's principal reliance, however, should shift to solar resources by 2025. In modest ways, this transition has already begun. It needs to be vastly accelerated if this timetable is to be met.

Heating and Cooling

Heating water with sunlight is simple The collector is, in essence, a box with a black bottom and a glass top Glass is transparent to sunlight but much less so to heat When the black bottom is struck by sunlight, it warms up, and this heat is trapped inside the collector. When water is pumped through the hot collector, its temperature rises The hot water is then piped to a very well-insulated storage tank where it is kept until needed

About 10,000 Cypriot homes, 30,000 American homes, 250,000 Israeli homes, and over two million Japanese homes have solar water heaters. In remote parts of Northern Australia, where fuels are expensive, solar water heaters are required by law on all new buildings. Niger requires them on all new hospitals, hotels, schools, and housing for government employees [13]

It is also simple to heat buildings with solar energy "Passive" solar homes have heating systems with just one moving part the earth, moving around the sun. Passive solar buildings capture sunlight where it strikes the building's walls and floor Such systems are designed to protect the structure from summer heat while retaining the sun's warmth during the winter Passive solar architecture is, beyond doubt, the most efficient and cost-effective way to heat and cool new buildings. Modest investments will often provide 80 to 100 percent of a building's heating and cooling requirements. But it demands advance planning, passive features cannot easily be added to existing structures.[14]

"Active" solar heating systems are more expensive, but they can be bolted onto the roof or southern wall of existing buildings as a substitute for—or supplement to—conventional furnaces In active systems, fans or pumps move solar-heated air or liquid from collectors to storage areas, from which the heat is drawn as needed Solar self-sufficiency will usually dictate a combination of active and passive features in the temperate regions of the world In the United States, about 4,500 homes and several hundred larger buildings now employ either passive or active solar space heating. The number has been more than doubling each year since 1974.[15]

Buildings can be cooled as well as heated by sunlight. Again, passive solar design is the most important first step; but active solar air conditioners are also now being marketed Fortuitously, absorption solar air conditioners reach peak cooling capacity when the sun burns brightest, which is when they are most needed They therefore could reduce peak demands on many electrical power grids As solar air conditioners penetrate the housing market, the overall economics of active solar heating systems will improve because solar collectors will begin providing a year-round benefit

Solar-thermal technologies have industrial applications as well. A study of the Australian food-processing industry, for example, found that heat accounted for 90 percent of the industry's energy needs Almost all this heat was at under 150° C and 80 percent was below 100° C, the boiling point of water Such low temperature heat can be produced and stored easily using simple solar devices Solar equipment has been applied on an experimental basis to various agricultural tasks in Australia, including a 56-square-meter solar heating unit for timber drying. In 1977, a commercial soft drink manufacturer near Canberra began using solar collectors In the United States, solar heating is now being applied to a soup-canning plant in California, a fabric-drying facility in Alabama, and a concrete block factory in Pennsylvania Solar-powered laundries and car washes are now operating in California, and a St. Louis brewery has turned to solar pasteurization.[16]

Throughout much of the industrial world, solar heating is now more economical than electricity That is to say, if the energy were to come from a *new* solar unit or a *new* nuclear or coal power plant, the solar investment would be cheapest The individual homeowner, of course, does not buy electricity just from the expensive new power plant, the utility averages the expensive new energy in with cheap energy from existing sources, so that the true cost of new power is hidden from the individual consumer (though borne, through rising utility bills, by all consumers) In Seattle, Washington, for example, the average price of residential electricity is now less than 1¢ per kilowatt-hour. But electricity from a new nuclear power plant would cost at least 7¢ per kilowatt-hour. At the lower, average prices, only the cheapest solar equipment is economical But compared to the higher cost for *new* power, virtually all solar heaters look attractive. For society as a whole, the additional energy could be most cheaply harnessed with solar equipment. It is thus in society's interest to encourage—and perhaps subsidize—individual and community solar purchases.

Even where the homeowner must compare the costs of *new* solar equipment with the *average* cost of competing energy sources, solar investments will generally make sense over the lifetime of a building. The most important first step is to incorporate passive solar design into the building's blueprints. Often this costs little or nothing. For example, it costs no more to place most windows in the southern wall than to place them facing north, but southern windows capture the sun's warmth while northern windows merely leak the building's internal heat Roof overhangs, masonry floors, and working shutters are not expensive When they are combined with tight construction and good insulation, they can lower the heating load of the building by 75 percent and more In Arkansas, 200 well-designed houses constructed under a grant from the U S Department of Housing and Urban Development cost no more than neighboring houses that were built using conventional construction standards, but their fuel bills are only one-fourth as high.[17]

More elaborate designs can lead to greater savings In the relatively mild climate of Atascadero, California, Harold Hay's passive solar house was constructed with bags of water incorporated on its roof.

These act like a "thermal flywheel," capturing the sun's energy on winter days and storing it to meet nighttime heating requirements In the summer, the system collects heat from the interior during the day and radiates it outward at night. The cost of these solar features was about $5,000—but the system has provided 100 percent of the home's heating and cooling needs for several years.[18]

In climates where passive solar design will not provide 100 percent of heating requirements, backup fuels or active solar systems are needed. In Princeton, New Jersey, architect Douglas Kelbaugh's passive solar home captures energy through a huge southern window wall during the day and stores it in a concrete interior wall that gives off heat during the night. Like other passive solar homes, the Kelbaugh residence employs no pumps or fans—just careful design. The solar features cost around $9,000, and they provide virtually all the home's requirements. In the unusually cold winter of 1976-77, the heating bill for supplementary conventional fuels in this comfortable northern residence was just $75 for the whole year. Financed with a standard home mortgage, Kelbaugh's solar energy system would require $1,800 cash at the time of construction with monthly payments of $60—far less than his neighbors' fuel bills.[19]

Active solar heating systems can be used to supplement the energy provided by passive solar design. Many different solar collectors, pumps, fans, and storage systems are now on the market, although their prices vary considerably Solar collectors can be built of durable metals for a materials-cost of about $20 per square meter. Princeton University physicist Ted Taylor believes the use of inexpensive plastic should make it possible to produce fairly durable collectors for a few dollars a square meter. In the United States, professionally installed active solar heating systems now range from under $100 per square meter to more than $700.[20]

Solar collectors at an installed-cost of $200 per square meter make economic sense when compared with the average costs of electrical resistance heating, except where cheap hydropower is plentiful. At $150 per square meter, they make sense compared with oil heat and electrical heat pumps. At $100 per square meter, they compete effectively with all residential fuels. The use of prefabricated units that are as easily installed as roofing could substantially reduce installation costs.[21]

In order to meet the solar heating goal of 20×10^{16} kilojoules per year by 2025, an ambitious program must soon be undertaken. The "passive" heating contribution assumes a nearly immediate decision to promote intelligent architecture. Schools of architecture and engineering should institute courses teaching the necessary skills, and appropriate training programs could be established in the construction industry. By 1985, all new buildings should employ passive solar design. In March 1978, the U.S. Department of Energy announced that it had under serious consideration a program to require that all new residences incorporate passive solar features. Since building stock turns over at the rate of about 2 percent a year, most of the world's built environment would incorporate at least some passive features by 2025. There remains additional scope for improvement in this area in subsequent years.

As well as supplementing passive designs, "active" systems can meet the special requirements for high-temperature heat in industry and agriculture, and for absorption air-conditioning. To calculate the amount of surface area needed as sites for solar collectors in order to meet the timetable, some assumptions must be made.

The amount of solar energy reaching different inhabited geographical locations varies by about a factor of three. The energy in the sunlight that falls on Stockholm each year contains about 3.5×10^9 joules per square meter. In some arid equatorial regions, however, annual insolation is about 10×10^9 joules per square meter.

In harnessing direct sunlight, the middle latitudes have a marked advantage in consistency over the polar regions. The Kenyan highlands, for example, experience only a 35 percent variation in insolation through the year. In Stockholm, on the other hand, 30 times as much solar energy per square meter is available in June as in December. Thus, far more collector surface will be needed to deliver a given amount of heat in the winter than in the summer. Moreover, the heat-

"By 1985, all new buildings should employ passive solar design."

ing required for buildings in Stockholm is obviously greater in the winter than in the summer. In order to capture the solar energy needed in winter, more collector surface must be installed than can be productively employed in the summer. (This disparity can be greatly mitigated by the use of seasonal storage of low-grade heat to warm buildings, but high-temperature industrial heat would be much harder to store for long periods.) So it is necessary to assume that only half the heat harnessed in solar collectors is actually put to productive use. Moreover, the collectors themselves do not capture and retain all the energy in sunlight that strikes them. Some is reflected off the glass or plastic cover, some leaks out of the collector itself. The calculations for this timetable assume that only half the energy that strikes the collector surface is captured, and that only half the energy captured each year is actually used.

Assuming the sunlight striking a typical collector each year contains 6×10^9 joules per square meter, an average square meter of collector surface would "deliver" one-fourth that amount, or 1.5×10^6 useful kilojoules per year. Thus, to meet the goals of the solar timetable, 20.0 billion square meters of collectors must be built by 1995, 40.0 billion by 2010, and 73.3 billion by 2025. If the average collector has a useful life of 25 years, about three billion square meters of new collector would be needed per year to maintain this level of direct solar heating. (It is hoped that collectors with longer life expectancies will have captured the market before 2025.)

These are large figures, but not so imposing that the goal should be dismissed as impractical. They are, however, sufficiently large to lead to the inescapable conclusion that solar features must be incorporated into the basic structural design of new buildings. Because these collectors would be mainly placed on the roofs of buildings, including factories, the expense involved could be dramatically reduced if all new roofs were constructed at an optimal angle to the sun with a broad southern exposure. This, in turn, may be related to such seemingly trivial considerations as whether communities build roads along due north-south and east-west axes, so that buildings along the road are well oriented to take advantage of the sun. In many such subtle ways, a successful solar transition will involve changing the face of the world.

Renewable Fuels

All fossil fuels were once green plants. Existing technology can harvest "energy crops" directly, without waiting hundreds of millions of years for nature to convert them into oil, gas, and coal. Dry plant material—biomass—contains about as much energy per ton as low-quality coal, and about 60 percent as much as high-quality bituminous coal The hydrocarbons produced by some plants contain as much energy as oil does.[22]

Because vegetation can be grown almost everywhere, it is relatively immune to international political pressures Unlike fossil fuels, biological energy resources are renewable, they can be grown as long as the land remains fertile and water is available Moreover, the use of biomass as commercial fuel involves few of the serious environmental drawbacks associated with the large-scale use of coal and oil. Although not given formal recognition in most official energy statistics, wood and charcoal currently contribute more than 15 percent of humanity's energy budget.[23]

To place the biological resource base in a broader perspective, the energy content of food, fiber, and lumber crops should be considered. In the United States, the potential energy contained in food, paper, and timber each year, when added to the potential energy in the residues of the related industries, equals more than half of all commercial energy use Yet barely 3 percent of this photosynthetic energy is now harnessed—virtually all by wood and paper companies.[24]

Biological energy sources can be divided into two broad categories. wastes from other biological processes (such as the food and fiber industries), and energy crops grown for use as fuels. Wastes are the easier source to tap for energy, since they must be disposed of in any case A variety of processes, including biogas production, pyrolysis, fermentation, hydrogasification, and hydrogenation, exist to convert organic wastes into high-quality fuels, and many cities and industries around the world have begun to tap their wastes for usable energy.

In the post-petroleum era, energy crops can be expected to make a far greater contribution to the global energy budget. A variety of trees, "Biologically-derived fuels can be directly substituted for the oil and natural gas that are in short supply."

grasses, and other types of vegetation have been suggested for intensive cultivation in energy plantations. Different crops will be appropriate for different climates, geographical areas, and energy uses. It also appears increasingly likely that energy crops can be successfully cultivated at sea and in freshwater bodies, thus making available for cultivation some of the 70 percent of the earth's surface covered by water.[25]

Renewable fuels constitute a particularly attractive component of a solar energy budget. They provide a compact way of storing large amounts of energy for very long periods; one gallon of alcohol contains more energy than is easily stored in 100 gallons of hot water in a conventional solar heating system. Moreover, biologically-derived fuel can be directly substituted for the oil and natural gas that are in short supply. For example, existing automobiles can operate smoothly on blends of gasoline with ethanol or methanol, and only minor engine modifications are needed to use pure alcohol fuel. Similarly, methane produced by biogas plants can be fed directly into existing natural gas pipeline systems. And for many purposes, charcoal manufactured from wood can serve as effectively as coke, which is produced from coal. A fair number of countries are already pursuing biological energy sources with vigor. China, for example, has built more than four million biogas plants in the last three years. These are designed to convert animal wastes and human excrement into methane—a clean-burning gas. Less aggressive biogas programs are being pursued by several other countries, including India, Indonesia, Korea, and Taiwan. The residue of the biogas process is an excellent fertilizer—far better than raw manure—and biogas plants also greatly assist the control of such communicable diseases as schistosomiasis.[26]

Brazil is engaged in a determined effort to substitute homegrown ethanol for 20 percent of its imported gasoline before 1985—a goal that will require the production of six billion liters a year. The first distillery built under the program is now producing 60,000 liters a day, 120 additional distilleries, ranging from two to four times as large as the first, are scheduled for construction by 1980. By 1995, Brazil hopes to substitute alcohol produced from sugar cane and cassava for all imported gasoline.[27]

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The net efficiency of biomass conversion processes will be of enormous importance to policy, but it will not be the sole criterion On occasion it is worth paying a premium to convert biomass into a form that is more useful. In the conversion of wood into methanol, for example, a large fraction of the original energy is lost, but because it is rather difficult to fuel an automobile with wood, the energy price is worth paying.

Moreover, the nature of any particular nation's biomass strategy will be determined by many factors specific to it the climate, water, soil, amount of available land, and so on The different types of fuels that are the logical end products will depend upon what crop is planted. In lieu of a detailed country-by-country inventory of potential energy crops and competing uses for land, and a clear determination as to whether ocean farming will prove feasible and ecologically acceptable, it is not possible to describe all the elements of a biomass strategy

Nonetheless, we can gain some idea of the magnitude of the effort needed by assuming that all the solid fuel will be wood, that all the liquid fuel will be alcohol, and that all the gaseous fuel will be methane. It must be recognized, however, that by 2025 it is likely there will be a variety of solid, liquid, and gaseous fuels from biomass in the commercial marketplace

Wood, when dried in the air, has an energy content of about 1.5×10^7 kilojoules per metric ton Hence, to meet the energy needs postulated for 1980, 2.6 billion metric tons of wood will be needed annually The 1995 target will demand 4 billion metric tons, the 2010 goal will need 4.6 billion, and the target for the year 2025 assumes the consumption of 5 3 billion metric tons of wood per year Currently, the net annual increment in forest growth is 36 billion tons, of which about 2 5 billion tons is used as fuel, with about 5.2 billion tons used by society for all purposes Thus, the amount of wood that would be used for energy in the year 2025 is about as high as is currently used for all purposes [28]

The productivity of different species under different conditions varies greatly, from a net growth of about two tons per hectare to more than 40 tons for intensively cultivated, short-rotation, fast-growing trees.

Some authorities believe that selective breeding and intensive cultivation could lead to yields on the order of 80 tons per hectare Assuming net annual growth of 12 tons per hectare on energy farms, the 2025 goal would require the employment of 440 million hectares for forest energy crops This represents about one-sixth of the land area now heavily forested and about one-eighth of all forest land It can also be compared with the 1.5 billion hectares currently under agricultural cultivation. This level of production appears sufficiently conservative to avoid the "mining" of forests now practiced in some locations, where forest stocks are depleted at a rate exceeding new biological production, causing diminution of the resource base. The overall efficiency with which this energy is ultimately used will depend upon the conversion process employed Most wood will probably be burned directly as a backup fuel for intermittent energy sources, though some will doubtless first be converted to charcoal, methanol, or other intermediate fuels possessing specific desired characteristics [29]

Ethanol has an energy content of 2.2×10^4 kilojoules per liter, and methanol somewhat less Assuming that an average facility produces 200,000 liters of alcohol per day, or 73 million liters per year, each such distillery will then produce fuel containing 1.6×10^{12} kilojoules per year Thus, if our goals for liquid fuels were to be met entirely by alcohol from such plants, the 1995 target would require the construction of 12,500 facilities The 2010 target requires 31,250 alcohol production facilities, and the 2025 goal would require 50,000

By the year 2025, it should be possible to grow crops yielding more than 3,000 liters of ethanol per hectare Sugar cane now produces between 3,000 and 3,400 liters per hectare in those regions where it can be successfully cultivated Increased yields could be achieved with new or improved species, with multiple cropping, or with improved conversion of crops into fuel However, assuming a yield of 3,000 liters per hectare, meeting the proposed 2025 liquid fuel target entirely from ethanol could require up to 1 2 billion hectares Again, comparing this with the 1 5 billion hectares now under agricultural cultivation worldwide provides a clearer idea of the enormity of this goal.[30]

Of course, all liquid fuels won t come from ethanol crops Methanol can be derived from a variety of sources, and ethanol itself can be manufactured from many organic wastes Several plant families yield a sap that is rich in complex hydrocarbons, and some of these plants can flourish in dry, inhospitable environments Yet the central fact remains the production of liquid fuels as substitutes for oil will be one of the most difficult tasks of the solar transition If it proves too difficult, liquid fuels will simply cease playing as important a role in human affairs as they now do

Methane contains about 4×10^4 kilojoules per cubic meter Hence, 500 billion cubic meters of methane are needed to meet the 1995 goal, 1 trillion cubic meters for the 2010 target, and 1 5 trillion cubic meters by 2025 The biogas produced by anaerobic digestion is only 50 to 60 percent methane, and most of the other gases produced have lower energy values Hence, more biogas will have to be produced to meet our targets than if it were pure methane The 2025 goal, for example, might demand over 2 trillion cubic meters of biogas.

About half of this methane can be obtained from the wastes of existing systems built upon biological products The remaining half could be derived from aquatic plants, such as fresh water hyacinths or giant ocean kelp If cultivated at sea, approximately one-fifth of 1 percent of the ocean surface would be needed. If successful, such kelp farms could also relieve some of the pressures put on the land by the demand for liquid fuels [31]

With wise management, the total energy attributed in this time frame to biomass fuels can be harvested on a sustainable basis It is less clear that there is scope for increasing production much beyond this level There is a popular tendency to think of renewable resources as infinite resources, but this is a confusion of size with duration If care is taken, biological crops can be cultivated in perpetuity But with short-sighted management, energy crops (like all other biological systems) can simply collapse

Already, vast treeless regions can be found in the Middle East, North Africa, Asia, and South America Multinational corporations and desperate villagers alike have too often failed to replant seedlings after

"There is a popular tendency to think of renewable resources as infinite resources, but this is a confusion of size with duration."

the harvest of mature trees If wood is to play a large role in the coming energy transition, successful reforestation programs must be among the world's highest energy priorities. Moreover, it is essential that reforestation programs be concerned with diversity and stability as well as yield Extensive monocultures could lead to dependence upon forests that are vulnerable to all sorts of threats Because several years of growth are required for the maturation of even short-rotation energy crops, the loss of such crops before harvest could be calamitous [32]

If pursued without foresight, as has too frequently occurred with the development of virgin lands, the biological resource base could be rapidly depleted Unless nutrients are recycled to the earth, the crops will effectively "mine" the soil Unless harvested areas are immediately resewn with good ground cover, flooding will strip away irreplaceable topsoil Unless conversion processes are carefully chosen and matched with crops, more energy will be used to produce a unit of renewable fuel than the fuel itself contains.

Even as they exhibit these various environmental vulnerabilities, biological fuels possess some unique advantages. Notably, unlike the fossil fuels that they could displace, renewable fuels would make no net contribution to atmospheric carbon dioxide. The plants that are the sources of these fuels draw as much carbon dioxide from the air during the process of photosynthesis as is returned to the air when the fuel is burned.

As part of an integrated, sensible strategy of producing energy in perpetuity instead of maximizing short-term production, the use of biological energy sources is one of the most attractive options available. They can provide the ideal buffers in the transition to a post-petroleum era because they are so similar in nature to the fossil fuels on which we currently depend so heavily

Electricity

Electricity is, in many respects, a splendid form of energy. It can perform a variety of tasks, from cooking an egg to powering a computer. Large amounts of electrical energy can pass through comparatively tiny wires, permitting the more efficient design of factories and other energy-intensive facilities Electricity is clean at the point of end-use, and it can be instantly available at the flip of a switch

On the other hand, electricity tends to be much more expensive than other forms of energy Electricity is difficult to store for long periods, and transmission grids are vulnerable to natural phenomena, common human error, and conscious malevolence. Major environmental costs are usually associated with the power plant and with the production of its fuel. It would therefore seem sensible to use electricity when it exhibits a marked advantage over competing forms of energy, and to look elsewhere when electricity holds no advantage

During the next 50 years, the use of electricity will almost certainly grow more rapidly than energy use in general This assumption is based in part on the belief that electricity will become available to hundreds of millions of people who do not currently have access to it. Partly, also, it is based on the assumption that more of the uses of energy that emerge in the next 50 years will rely on electricity than on other energy sources. On the other hand, these estimates of the growth rate for electricity are far lower than those forecast by most proponents of a nuclear- or coal-dominated future They include the assumption that a series of foreseeable technical advances will make solar-electric technologies sufficiently inexpensive for the proposed levels of usage to be economically practicable. If this assumption proves in error—if cost reductions do not occur as rapidly as expected —either the total use of electricity will be lower, or some fraction of the chemical fuel supply will have to be allocated to electrical generation, or both.[33]

Currently, the most commonly harnessed solar source of electricity is hydropower (although limited amounts of sugar cane residue, organic municipal wastes, wood, and even coconut husks are also converted into electricity). In 1976, hydropower was the source of 72.6 percent of all Canadian electricity Most surveys suggest more hydroelectric development globally than would actually be feasible Conventional surveys too often ignore the flooding of fertile agricultural bottom lands, and plan for the construction of dams in geologically unstable areas (where they may rapidly fill with silt) The more conservative assumption used in this timetable is that global hydroelectric capacity will increase fourfold in the next 50 years. Wind power and solar photovoltaic cells are expected to shoulder the bulk of the remaining electrical generating burden, although ocean thermal-electric stations could provide an attractive supplement if their economic costs and environmental consequences prove acceptable.[34]

Wind turbines once provided significant amounts of electricity. In 1916, Denmark had more than 1,300 operating wind generators. By 1940, the United States had built about six million Before the American rural electrification program, wind turbines were the only source of electricity available to much of rural America. But cheap fossil fuels and inexpensive hydroelectric facilities, combined with large federal subsidies for integrated electrical grids, priced wind power out of the marketplace in a matter of years. However, now that the cost of fossil fuels is rising dramatically, wind power is once again beginning to receive serious international attention Many interesting new technologies are being pursued, including vertical axis windmills that turn in the wind like spinning coins In many parts of the world, electricity generated from the wind already makes economic sense With declining costs brought about by mass production and technological innovation, the use of wind power can be expected to increase rapidly, first in rural areas of the developing world and then in the most wind-rich parts of the industrial world.[35]

The most exciting solar-electric prospect is the photovoltaic cell, a simple device that generates electricity directly when sunlight falls on it. Photovoltaic cells have no moving parts, consume no fuel, and produce no bomb-grade materials Fashioned from relatively abundant elements, they have long lifetimes, and require little maintenance.[36]

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, they are most sensibly used in a decentralized fashion—perhaps incorporated in the roofs of buildings—so that transmission and storage problems can be minimized. With decentralized use, solar cells can be efficiently combined with compatible technologies to use waste heat for space heating and cooling, water heating, and refrigeration.

In the summer of 1977, a photovoltaic array in Mead, Nebraska irrigated 80 acres of corn at 1,000 gallons per minute.

The manufacture of photovoltaic cells is currently a low volume business and the products are consequently rather expensive But with mechanized mass production, costs should plummet, they are, in fact, already falling rapidly Solar cells cost about $200,000 a peak kilowatt in the late fifties By early 1975, the costs had dropped to $31,000, by September 1976, the figure was $15,500. In early 1977, the cost of solar cells fell to $11,750 a peak kilowatt And in December 1977, an Arkansas Community College contracted for a photovoltaic system for $6,000 per peak kilowatt Making allowances for the average availability of sunshine versus the average capacity factor of large nuclear power plants, and considering costs and losses during transmission and storage, solar cells are now probably about ten times as expensive as nuclear power in the most favorable regions of the United States. Solar cells now cost about one-tenth of what they cost five years ago, nuclear power now costs about twice as much as it cost five years ago [37]

The earth now has about 100,000 megawatts of nuclear capacity and about one megawatt of photovoltaic capacity With mass production, solar cell costs are expected to continue falling dramatically The current goals of the U S Department of Energy are to drive prices down to $2,000 per peak kilowatt by 1980, $500 per peak kilowatt by 1985, and $100 to $300 per peak kilowatt by 1990 At present prices, solar cells make economic sense for remote applications of various kinds, at 1985 prices, they will be cost-effective for peak power production in much of the industrial world, and at 1990 prices, they should experience the kind of market penetration needed for a successful solar transition. With a substantial international effort, the pace of these cost reductions might well be accelerated.[38]

One kilowatt-hour of electricity equals 3,600 kilojoules Hence, to meet the 1995 target for electricity from renewable sources, 5.6 trillion kilowatt-hours would have to be generated by then per year. The 2010 goal would require 12.5 trillion kilowatt-hours, and the 2025 target would need nearly 28 trillion kilowatt-hours In comparison, "Solar cells now cost about one-tenth of what they cost five years ago."

current worldwide production of electricity from all sources is about seven trillion kilowatt-hours.

For hydroelectricity, this assumes that additions roughly equal to the current installed capacity will be made every 15 years Assuming that average wind turbines have a rated capacity of 500 kilowatts allows some estimation of the needed effort in wind power (These would produce enough electricity to meet the current demand of about 200 average homes in the United States) These turbines would be located on sites with sufficiently steady wind to produce power at an average of 40 percent of their rated capacity. Under such assumptions, the 1995 wind-power goal would require 800,000 windmills. The target for 2010 will demand some 1.6 million wind turbines, and by 2025 nearly 5 million wind turbines must be operating Thus by 2025, the world would have about as many large wind turbines as there were small windmills in the United States in 1940 [39]

By 2025, significant amounts of electricity should be available from various solar-thermal devices, including small, low-temperature engines using organic working fluids. It is also possible that large power plants will be using the temperature differences between ocean gradients to produce steady, round-the-clock power But an assumption that all the solar-electric power will be derived from solar cells allows a rough sense of the magnitude of the required effort

Averaged worldwide and over an entire year, a kilowatt of photovoltaic capacity should produce some six kilowatt-hours of electricity per day. To achieve the 1995 solar-electric goal will require the production and installation of 1.2 million megawatts of photovoltaic capacity. The 2010 goal will need almost 4 million megawatts of capacity, and the 2025 target anticipates a photovoltaic capacity of about 7 5 million megawatts.

Getting There from Here

Solar energy is now receiving far more international attention than ever before. A recent survey found formal solar research programs in

63 countries. Clearly the leader in research spending is the United States, with a current budget approaching $400 million and reasonable prospects for double that amount in 1979. Yet for all the public
30 interest and enthusiasm, the mainstream energy establishment has remained rather aloof. Even the high U.S budget represents a mere 4 percent of federal energy research and development spending Few planners have devoted the sort of time and attention to renewable resources that they have given to nuclear energy or coal—even in countries rich in sunlight but with no domestic reserves of uranium or coal. Only a handful have examined what an aggressive solar path might look like.[40]

Sweden is one that has. The Swedish Secretariat for Future Studies has mapped out in some detail a path that Sweden might follow in order to be entirely dependent upon renewable energy resources by 2015. The report, *Solar Sweden,* assumes that total energy use will increase 37 percent by 2015, and that the existing nuclear facilities will have finished their useful lives by then and been replaced by solar technologies. Of the total energy used, 62 percent would be derived from biological resources, 13 percent from solar heating, 11 percent from hydropower, 9 percent from photovoltaics, and 5 percent from wind power.[41]

Under the Swedish plan, biological sources will require between 6 and 7 percent of the land area of the country. Photovoltaic cells will be placed on the roof areas of densely populated districts. The wind component will require the construction of 250 four-megawatt wind turbines—the energy equivalent of a large nuclear reactor—every year. Two-thirds of the Swedish energy research budget for 1978-81 is concentrated on renewable sources Nuclear fission and nuclear fusion, by comparison, each receive only 12 percent of the Swedish federal energy research budget Although the results of this study have not yet been folded into official policy, the prospects for a solar Sweden have at least been officially scrutinized and found plausible

Japan, on the other hand, is manifestly on an unsustainable energy path but has given little serious attention to a possible change of course. Now utterly dependent upon foreign sources of fuel, Japan hopes to produce domestically 15 percent of its energy needs by 1985, and 22 percent by the turn of the century. These modest projections are misleading, however, because two-thirds of domestic energy would come from nuclear power, which is "domestic" only in a very loose sense since the country must import uranium. Yet, an energy growth rate of 5.2 percent per year is forecast through 1984, and 3.0 percent growth is expected from 1985 through 2000.[42]

The official energy plan in Denmark, unveiled in 1976, showed renewable energy resources constituting just 4 percent of the national energy budget by 1995. Scientists and engineers from leading Danish universities subsequently prepared an alternative energy plan, under which the contribution from renewable sources would be tripled. The alternative plan, produced under very conservative assumptions, effectively undercut the government's rationale for major investments in nuclear power and led to a postponement of the official commitment to nuclear energy.[43]

In Britain, the House of Commons Select Committee on Science and Technology reported in 1977 that the Department of Energy "must accord greater priority to renewable sources in view of their potential importance." It urged the establishment of specified "target dates" for development of working projects "so that those renewable sources which prove to be technically and economically viable are in a position to begin making a worthwhile contribution to the United Kingdom energy requirements by 1990." This report has not had much policy impact as yet, however. The British Department of Energy is funding the world's most ambitious project for harnessing "wave power," but it remains unexcited about other renewable energy resources.[44]

A report by the Australian Academy of Science recommended that federal research on solar energy and bioconversion be greatly increased. As a target, the report suggested that more than one-fourth of all primary energy be derived from solar resources—chiefly solar heaters and liquid fuel from biomass—by the year 2000. The Commonwealth Scientific and Industrial Research Organization has in fact been sponsoring solar energy research for more than 20 years. In the last few years this research effort has begun to see practical application. Today, about 30,000 Australian homes employ some sort of solar technology—mostly water heaters, the production of which has increased fivefold since mid-1976.[45]

32 If eucalyptus were used to meet the goal of the Australian Academy for alcohol fuel for automobiles, about 200 million tons of wood would be needed each year. Seventeen factories, each associated with a 740,000-hectare plantation and capable of producing 4,000 tons of alcohol per day, would be constructed. If sugar cane were the energy crop, only one-fourth as much land would be required, but seasonable storage could pose problems. Some combination of crops would doubtless be optimal.

The government of Brazil is actively pursuing a similar course already. It is encouraging the substitution of alcohol, produced from sugar cane and manioc, for 20 percent of the country's gasoline by the early eighties, and for 100 percent of imported petroleum fuels as soon as possible. Sixty billion liters of alcohol would be required to replace current consumption of gasoline, diesel, and fuel oil. Annual production is only 740 million liters of alcohol today, but the program is growing rapidly. To produce 60 billion liters, about 4 percent of the land area of Brazil may have to be dedicated to energy crops.[46]

It is difficult to ascertain China's energy strategy for the future, but it is clear that at least some renewable energy technologies are being pursued vigorously. With 60,000 mini-hydroelectric facilities and 5.4 million biogas plants, China is the obvious world leader in both areas. Passive solar greenhouses are used extensively, and the climate in China is ideal for applying passive solar design to houses as well.

Diverse lands with different geographies, climates, and cultures are turning toward the sun. This is no cause for surprise. The resource base is abundant. Many proven technologies can be employed to harness renewable energy sources. Tapping such resources avoids many of the more disturbing consequences of conventional energy growth. The important question is no longer whether solar energy will be developed. The questions today are, How much and how soon?

No insurmountable technical or material difficulties will hinder the solar transition. The major long-term constraint appears to be competition for land, especially for energy crops versus other crops. Some important questions remain outstanding, such as the net energy delivered by some solar processes, and the possibilities for innovative ways to store sunlight We have solutions in hand for all these problems, but they are not necessarily the best possible solutions. Nonetheless, we know enough to proceed, realizing that improvements will emerge over time.[47]

Many social questions—some of them trifling, some of them momentous—must also be resolved What effect will solar energy have on employment? Studies in the United States found that solar technologies produce more jobs than any other energy sources, Brazilian studies of ethanol production suggest that it will be highly labor-intensive as well As solar electricity becomes cost competitive, what changes will there be in the regulation of utilities, and in the relation of the utility to its community? Some utilities may try to monopolize the sun, others may decide to oppose it How is capital to be made available to the family or neighborhood at rates that make purchases attractive? How are warranties to be established for items that may make economic sense only after seven years of use? Whose aesthetic judgment will prevail regarding the attractiveness of various pieces of equipment?[48]

A transition to an efficient, sustainable energy system is both technically possible and socially desirable But 150 countries of widely different physical and social circumstances are unlikely to make such a transition smoothly and painlessly Every potential energy source will be championed by vested interests and fought by die-hard opponents Bureaucratic inertia, political timidity, conflicting corporate designs, and the simple, understandable reluctance of people to face up to far-reaching change will all slow the transition down. Even when clear goals are widely shared, they are not easily pursued. Policies tend to provoke opposition, unanticipated side effects almost always occur.

If the path is not easy, it is nonetheless the only road worth taking. For 20 years, global energy policy has been headed down a blind alley

It is not too late to retrace our steps before we collide with inevitable boundaries. But the longer we wait, the more tumultuous the eventual turnaround will be

Notes

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7. Ted Greenwood, Harold A Feiveson, and Theodore B Taylor, *Nuclear Proliferation Motivations, Capabilities, and Strategies for Control* (New York McGraw-Hill, for the Council on Foreign Relations, 1977), Nuclear Energy Policy Study Group, *Nuclear Power Issues and Choices* (Cambridge, Mass Ballinger Publishing Company, 1977) The figures on missing bomb-grade materials were in previously classified studies of the U S Nuclear Regulatory Commission and the Energy Research and Development Administration that were released as a result of a Freedom of Information suit, as reported in *Nuclear Info*, a publication of the Atomic Industrial Forum, August 1977

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28. Earl, *Forest Energy*

29. Mitre Corporation, *Silvicultural Biomass Farms* (Arlington, Va 1977) While 12 tons per hectare is not an arbitrary figure, it is also not a "hard" number It is an optimistic, though plausible, judgement regarding the likely average worldwide yield of biomass farms 50 years hence If high-yield, nitrogen-fixing trees that can flourish on marginal land with minimal care are bred, this estimate could prove conservative If, on the other hand, no significant advances in silviculture are successfully propagated over the next five decades, the 12-ton figure will prove too high (Although much higher yields than this are already being achieved on test plots, record agricultural yields from small plots are often four to eight times higher than average yields See C C Burwell, "Solar Biomass Energy An Overview of U S Potential," *Science*, March 10, 1978.)

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