By JERRY GREY
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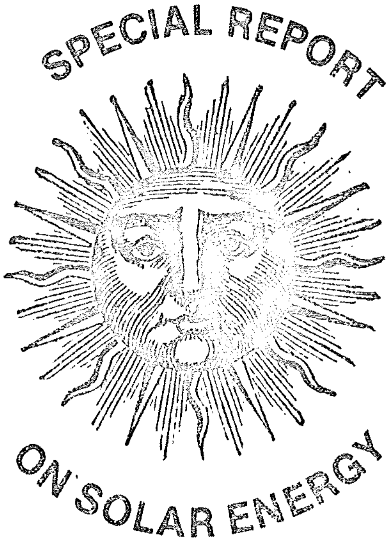
Energy Since the Oil War

AN INTRODUCTION TO



SPECIAL REPORT ON SOLAR ENERGY

Two years ago in August 1973 *A/A* published a comprehensive series of articles on advanced energy concepts under the title, "Prospecting for Energy." Much has happened since. The Arab oil embargo following the October 1973 Mid-East war triggered the famous "energy crisis," which brought about creation of a Federal Energy Administration (FEA) and, later, an Energy Research & Development Administration (ERDA). A thousand or so bills on energy were introduced in the U.S. Congress, and perhaps several times that many in the various state legislatures. The old, relatively obscure House Committee on Science and Astronautics revised its charter and, principally by picking up the hotly contested jurisdiction over energy legislation became the all-powerful Committee on Science & Technology.

A spate of studies on "energy policy" during this period[1-3] appeared to have little or no effect on national energy policy. Although frequently reinventing the wheel, they *did* serve to highlight problems and subject them to relatively careful technical, economic, and institutional scrutiny.

This scramble of activity in the suddenly popular field of energy culminated in June 1975 with the issuance by five-month-old ERDA of a significant document labeled "A National Plan for Energy Research, Development, and Demonstration." Subtitled "Creating Energy Choices for the Future," the ERDA Plan, as it is familiarly called, identifies five national goals in energy:

- To maintain the security and policy independence of the Nation.

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A sense of urgency spurs creation of the Energy Research and Development Administration (ERDA); the new agency issues a master plan; and solar power gains a higher priority in the government and public eye

- To maintain a strong and healthy economy, providing adequate employment opportunities and allowing fulfillment of economic aspirations (especially in the less affluent parts of the population).
- To provide for future needs so that life styles remain a matter of choice and are not limited by the unavailability of energy.
- To contribute to world stability through cooperative international efforts in the energy sphere.
- To protect and improve the Nation's environmental quality by assuring that the preservation of land, water, and air resources is given high priority.

ERDA also issued a broad program for implementing its plan.[5] Both the plan and this program clearly recognize solar energy, along with fission breeding and nuclear fusion, as one of the three "inexhaustible [energy] sources for the long term." Nevertheless, the implementation program for solar energy (as well as other energy disciplines) leaves much to be desired. This weakness perhaps results from ERDA's youth as well as the way it was formed by the total absorption of all non-regulatory and non-military AEC activities and the agglomeration of various programs from other agencies, such as the National Science Foundation's energy projects and several Department of Interior functions including the Office of Coal Research. Perhaps after the agency has had time to sort out its various missions and its personnel have had a chance to "grow into" their new jobs, a proper maturing of the ERDA plan will become evident. As required by Section 6 of Public Law No. PL 93-577,[6] ERDA will update the plan annually.

Because of the national concern about energy matters, several Congressional committees asked the U.S. Congress's Office of Technology Assessment (OTA) to review the ERDA plan exhaustively. This comprehensive critique[7] sets the stage for the detailed *Astronautics & Aeronautics* Special Report on Solar Energy which follows.

OTA reviewed five areas corresponding roughly to ERDA's divisions: fossil; nuclear (including fusion); solar, geothermal, and advanced energy sources (including research); conservation; and environment, health, and safety. From OTA's findings I have culled developments that have taken place in each of these fields since the August 1973 *A/A* "Prospecting for Energy" article.

In fossil fuels accelerated emphasis on coal gasification and liquefaction, as well as direct utilization, is the principal new development. Little qualitative progress has taken place since 1973, although major steps in the "demonstration" phase of RD&D (Research, Development, and Demonstration) have been formulated. Oil shale development remains in the research phase while active pursuit continues of enhanced recovery of oil and gas by hydraulic fracturing, fluid injection and other advanced methods. ERDA has these goals for annual U.S. energy conversion from fossil fuels in quadrillions of Btu (quads):

Energy Source	**1985**	**2000**
Coal gasification and liquefaction	~0	>9
Direct coal utilization	>6	>9
Oil shale	< 2.5	< 4.5
Enhanced oil/gas recovery	>6	>9

OTA criticized the ERDA fossil-fuel program principally for giving insufficient attention to technologies available in the *near* term—oil/gas recovery enhancement and production of synthetic oil and gas from coal and oil shale—and placing far too little emphasis on the institutional and other nontechnical constraints to fossil-fuel use, particularly by not using the systems approach to the development of each energy source.

The ERDA plan covers three areas of nuclear RD&D—nuclear converter reactors, nuclear breeder reactors, and fusion. Major efforts have begun on converter and breeder safety, in conjunction with the Nuclear Energy Regulatory Commission, and have become a major factor in all ERDA nuclear planning. The controversial Rasmussen report on light-water nuclear converter powerplants[8] had surprisingly little impact on either safety policy or public reaction. The recent Harris poll,[9] which revealed unexpected public support for nuclear power, appears to identify potential energy shortages as the principal factor in public thinking, rather than safety.

The U.S. breeder program appears to be staggering along a tortuous path between future needs (ERDA identified the breeder as one of the three "inexhaustible" sources for the long range[4]), environmental concerns (particularly plutonium proliferation), and economic viability. Meanwhile, France has built and operated its Phenix breeder with great success,[10] and appears to be gaining a world position in breeder reactor technology comparable to the present dominant world market position of the United States in commercial aircraft. A recent GAO study decries the high cost of the U.S. breeder[11], but supports ERDA's contention that it forms an essential element in the long-range U.S. energy-supply picture.

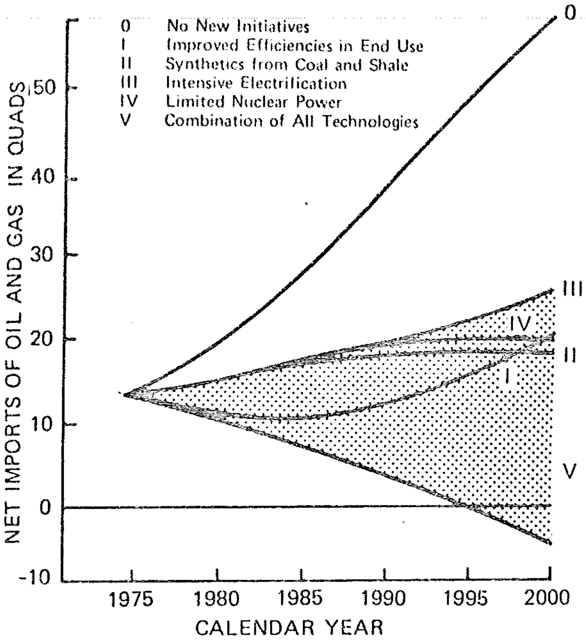
The U.S. fusion program continues to strengthen in both breadth and depth. Although the promise of inertial containment (laser fusion) has decreased somewhat since 1973, magnetic containment research has expanded to include the General Atomic doublet (non-circular toroidal crosssection) in addition to the existing Tokamak, Ormak, mirror, and Theta Pinch concepts. The Tokamak Fusion Test Reactor program has begun at Princeton, and will for the first time use the fusion fuels tritium and deuterium. More about fusion later.

ERDA has these goals for nuclear power generation (figures in quads):

Energy Source	1985	2000
Nuclear converter reactors	>6	>9
Nuclear breeder reactors	0	~0
Nuclear fusion	0	0

OTA's main concerns about the ERDA program in nuclear power centered on evaluating uranium resources; the need for an early decision (and demonstration) of waste disposal in salt, considered by OTA to be technically feasible; the need for ERDA to examine other breeder reactor concepts than the liquid-metal and light-water designs; lack of adequate technology programs on thorium breeders and high-temperature gas-cooled reactors; and the need for more caution in rapidly moving fusion research.

ERDA's program management has lumped under "conservation" not only subjects which would normally be appropriate there, such as improved thermal insulation, enhanced efficiency of end-use devices, and improved transportation efficiency, but also new energy-conversion concepts, energy storage and transmission, conversion of waste materials, and electric transportation technology. Almost all these areas have seen major developments since 1973; although too numerous for discussion here, the developments are well outlined in the ERDA plan and program.[4,5] ERDA has these goals for annual national energy savings (figures in quads):



ERDA's plan for the nation's energy future is based on the five scenarios illustrated in this chart. This approach—setting the reduction of oil and gas imports as the principal goal—has received considerable criticism. Another criticism is the timidity of ERDA's program for reducing energy consumption (Scenario I in the chart). Currently, the United States still remains firmly fixed at Scenario Zero.

Energy Saving Source	1985	2000
Conversion of waste materials	<2.5	4.5-9
Electric conversion efficiency improvement	0	<4.5
Electric power transmission and distribution	0	<4.5
Electric transportation	0	<4.5
Transportation efficiency improvement	2.5-6	4.5-9
Industrial energy efficiency improvement	2.5-6	4.5-9
Conservation in buildings and consumer products	2.5-6	4.5-9

OTA criticized the conservation program mainly for its low funding and timidity, as well as a lack of focus on the immediate problems of end-use efficiency. OTA noted a strong potential influence of non-technical constraints, as well as the urgent need for close cooperation with other federal agencies, state and local administrations, and industry.

As might be expected, the ERDA plan clearly spells out a strong program to determine and mitigate near-term environmental problems, such as air pollution from combustion, effects of expanded coal mining and offshore oil drilling, nuclear waste disposal, safety, and radiation releases from nuclear powerplants, and especially pollution of water resources. The plan also specifically recognizes the need for a detailed environmental assessment *before*

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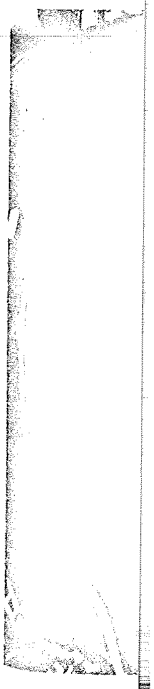


demonstrating new technologies, and for a strong drive to inform the public and coordinate actions with state and local agencies and other federal offices such as EPA.

OTA faulted the plan for lack of attention to the change in scale of environmental problems due to the great increase in fossil-fuel use, particularly coal, to the energy cost of necessary environmental regulations, to the global impact of new energy technologies, to environmental impacts of manufacturing the new synthetic fuels, and to the serious water resource problem from an overall systems viewpoint.

The solar, geothermal, and advanced-technology portion of the ERDA plan directly concerns us in this *Astronautics & Aeronautics* special report. Although ERDA has only recently appointed Henry H. Marvin of GE as director of its Solar Energy Division, that competent group, which it inherited principally from the National Science Foundation, has developed a substantial solar program described not only in the ERDA plan[4] and program[5] but also laid out in considerable detail in two ERDA documents dealing solely with solar energy.[12,13]

T-1 ERDA'S PROJECTION FOR FUTURE CONTRIBUTION OF SOLAR ENERGY
In 10^{15} Btu (quads).

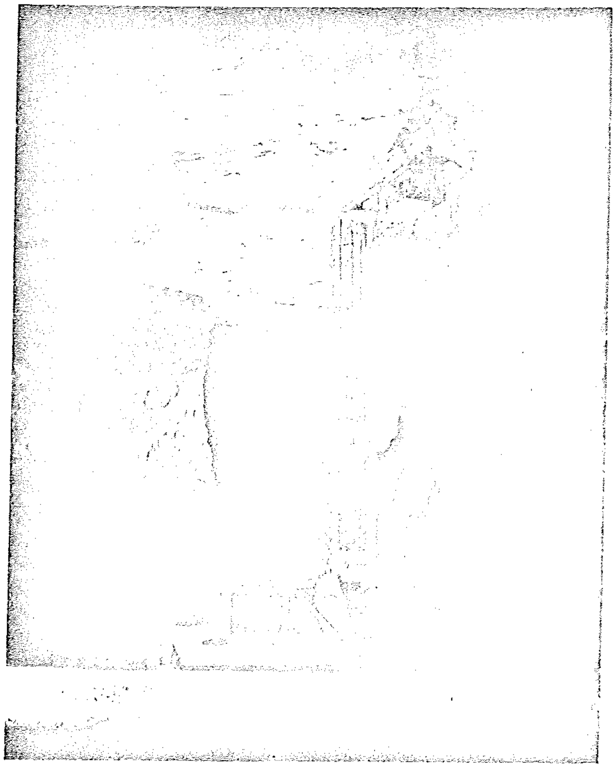
Category	1985	2000	2020
Direct thermal use	0.2	3	20
Solar electric	0.07	5	15
Biomass fuels	0.5	3	10
Total U.S. demand	100	150	180
Solar % of U.S. demand	0.8%	7%	25%

Long-distance electric power transmission—e.g., from satellite solar power rectennas, sea solar power plants, or desert-located solar thermal-electric plants—could be more economical by direct (dc) rather than alternating current (ac). This new liquid-metal plasma valve is a key component in a high-voltage dc transmission system.

The nuclear-fusion program is a classic example of a high-potential but also highly uncertain option for long-term solutions to the world's energy needs. It has been well supported by major Federal budget commitments, both currently and over the past 20 years, as typified by the Princeton Large Torus—the latest and largest of a series of promising "tokamak" (toroidal geometry) experiments aimed at demonstrating that nuclear fusion is physically achievable.

The thermal energy in "hot rock" thousands of feet below the surface represents an enormous potential reservoir to help meet our national energy needs. Learning how to extract this energy safely and economically is a major (and long-term) effort now being undertaken by several agencies, since "conventional" geothermal energy sources (hot water or steam) are severely limited in their potential utilization.

ERDA covers five basic subjects in this category: direct thermal utilization of solar energy, solar electric power, fuels from biomass, geothermal power, and basic research. Of the five, this issue covers the first three at length. In basic research ERDA emphasizes molecular sciences (energy process control), materials sciences (high-temperature and special materials), nuclear sciences, and high-energy physics (fundamental processes of nature). Unfortunately, the program inherited from the AEC takes by far the lion's share of the budget devoted to high-energy physics. Although certainly extremely important to the nation's overall research effort, high-energy physics has little relevance to the bulk of ERDA's mission. This distortion, along with the necessarily inherited AEC practice of separating basic and applied research, has drawn most of the OTA criticism of ERDA's basic-research effort.



Oil shale represents a large potential energy source, but suffers from severe environmental and economic problems. One possible solution, *in situ* (underground) retorting, is receiving the bulk of ERDA's attention, but its widespread utilization, even if proved practical, is clearly "well down the pike." Much new equipment and totally new mining techniques are required.

In the geothermal field, ERDA plans to expand existing moderate-temperature plants and resources (described in the August 1973 *A/A*), and explore more advanced technologies such as geopressured reservoirs and deep "hot-rock" thermal resources. The OTA panel saw the principal stumbling blocks to harnessing geothermal energy as primarily legal and institutional rather than technological, and therefore requiring considerable cooperation by ERDA with the Federal Energy Administration and with state and local agencies. The ERDA plan calls for about 1 quad per year of geothermal energy by 1985 and 2.5-6 quads by 2000, goals which the OTA panel considered highly optimistic unless major direct use of geothermal heat becomes prevalent in addition to generating electric power from it.

The ERDA plan for solar energy takes three directions: toward thermal utilization, electric power generation, and biomass fuels. ERDA sets out its view of the potential capabilities of these three areas in T-1.[12] Each technology contributing to these areas forms the subject of one of the articles in this issue of *A/A*—solar heating and cooling, solar-thermal electric power, photovoltaic power, wind power, ocean thermal energy conversion, and fuels from biomass. And here we include an article on the satellite solar power station (SSPS) which ERDA specifically omitted. In fact, *no mention* of space-based power systems for terrestrial use appears anywhere in ERDA's plan,[4] program,[5] or definition report.[12]

This omission of a technology having major potential impact on the world's energy future is surprising in view of the plan's title, "Creating Energy Choices for the Future." Of course, today a SSPS would cost much too much. AIAA's Assessment, *Solar Energy for Earth*, the summary portion of which follows this introduction, says the SSPS should be considered only as a prospect for widespread use in "the first half of the 21st Century." Nevertheless, the SSPS *is* technically feasible; it *does* have enormous potential benefits, and NASA's recent "Outlook for Space" study included it as one of only two future projects specifically identified. It would appear, therefore, that ERDA should at least recognize SSPS by allocating suitable funds for systems studies, physical research, or component development.

This curious omission spurred OTA's review panel to question the whole basis on which ERDA makes programmatic decisions on systems having

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AIAA ROLLS UP ITS SLEEVES ON ENERGY

Although the AIAA has recently accelerated its activities in energy programs, the Institute is not by any means a new rider on the energy bandwagon. For many years the AIAA technical community has quietly pursued a broad spectrum of energy-related work, and the Institute can now draw on these well-developed technical capabilities in its current energy program.

Examples of fields in which AIAA has had long and particularly extensive experience, and which specifically apply to the ERDA mission include:

Efficient combustion of fossil fuels

New fuel development, processing, and handling, most notably hydrogen

New engine concepts, such as hydrogen-fueled automobiles, fluidized-bed combustors, and high-pressure open- and closed-cycle turbine engines

High-energy lasers, as would be used for fusion power

Cryogenic systems

Microwave and laser power transmission

Advanced electric power systems for space

Photovoltaic converters, arrays, and power systems

Synchronous-orbit power systems

Focusing solar collectors and high-temperature absorber subsystems

Transmission of thermal energy by heat pipe

Wind power

Energy storage such as by advanced batteries, flywheels, and hydrogen

Energy system analysis

MHD power generation

Thermionic converters

Aircraft fuel economy

Advanced ground transport, such as high-speed trains.

Applying this broad technical background to today's critical energy situation has progressed slowly. The AIAA has, of course, cosponsored for many years such joint activities as the annual Intersociety Energy Conversion Engineering Conference. A few years ago the predecessor of the current intersociety Coordinating Committee on Energy was formed, with the AIAA as a charter (and still extremely active) member.

Within the Institute, the Technical Activities Committee (TAC) has long maintained a Technical Specialty Group (TSG) on Non-Chemical Power and Propulsion (recently converted to Energy Systems). TAC originated a number of AIAA-designed and operated technical programs, such as the Energy sessions and workshops at the AIAA's three Urban Technology Conferences in 1971-73, the 1974 Aircraft Fuel Conservation Workshop Conference, and this year's *AIAA Assessment of Solar Energy for Earth.*

In the summer of 1975, TAC took a major step toward formalizing these miscellaneous efforts by establishing an AIAA Energy Activities Task Force, led by TSG coordinator for energy systems Robert L. Gervais of McDonnell-Douglas Astronautics. The Task Force's directive charged it not only with serving as the center for AIAA energy activities, but coordinating with and supporting ERDA's efforts in those areas where the AIAA's technical strengths could be most effectively applied. Toward this purpose, Gervais set up five Task Force Committees corresponding to ERDA's subject areas and assigned them to chairmen as follows: **Fossil Fuels,** George Pedersen of Allison; **Nuclear,** J. Preston Layton of Princeton Univ.; **Solar, Geothermal, and Advanced,** two committees, one for **Solar, Geothermal, Thermionic** under Harrison Killian of Aerospace Corp.; and a second **Fusion, MHD** under Kenell Touryan of Sandia Labs.; **Conservation,** Herbert Fox of N.Y. Inst. of Technology; and **Environment and Safety,** Thomas Kastner of Grumman Aerospace.

Each Committee is now setting up its program, in close coordination with the appropriate ERDA assistant administrator or division head. The Committees have as major goals to explore the potential of gaining AIAA members in the rapidly expanding energy disciplines appropriate to AIAA; to suggest, organize, and operate both open specialist meetings and workshop conferences; to formulate AIAA Assessments or other position papers; and to communicate the information brought forth by these activities to both the public at large and to key technical and nontechnical organizations nationwide. AIAA proposed to the intersociety Coordinating Committee on Energy as one interesting possibility establishing a new intersociety *Journal for Energy Research, Development & Applications.*

The AIAA's Energy Activities Task Force represents the Institute's long-term commitment to leadership in many of the energy technologies which will continue to be major national and global concerns for years to come. Any AIAA member who wishes to participate in local activities of the Task Force in his community should contact Jerry Grey at AIAA headquarters. If enough members show interest, the AIAA will organize Section counterparts to the national Energy Activities Task Force. Let us hear from you.—**J.G.**

potentially large payoffs but which entail major technological or economic uncertainties. It cited ocean thermal electric conversion (OTEC) and the nuclear-fusion program as further examples. Of the three, the only one not yet known to be technically feasible—fusion—is the only one receiving substantial support. In FY76 some $165 million, not including military laser efforts, goes to nuclear fusion.

True, ERDA inherited from the AEC a fusion program twenty years old. Yet the fat budget of the fusion program compared to $5 million doled out to ocean thermal energy conversion, which employs much less advanced technology, has raised eyebrows. Even in comparison with the SSPS, which has been shown to be technically if not yet economically feasible, nuclear fusion appears to suffer. Not only is fusion not yet feasible technically, but it also is subject to the same level of economic uncertainty as the SSPS. Both seem headed for wide application no earlier than the first half of the 21st Century.

Not that the fusion program should be stopped or replaced by OTEC or SSPS. It should be sustained at about the present level of effort through a technical feasibility (or infeasibility) demonstration. However, this funding does not jibe with that going to the OTEC concept, and certainly not with ERDA's complete dismissal of the SSPS concept.

OTA further criticized the ERDA solar-energy plan for underemphasizing solar heating and cooling, which represents not only the earliest prospect for massive use of solar energy, but also a substantial long-range application, and for overemphasizing electrification, although thermal energy accounts for over half the current energy demand, and transportation for over half of the remainder.

OTA also pointed out the lack of any program for generating synthetic fuels other than by biomass or waste conversion.

The articles which follow derive from AIAA's most recent assessment, *Solar Energy for Earth*, published in April. They have been updated to include information presented at the AIAA/AAS Conference on Solar Energy for Earth and developments in the field since then. The assessment's recommendations and summary are still valid. We reproduce them on the following pages just as they appeared in the original.

AIAA will continue its work in energy. A brief review of its new energy-activities program appears boxed on one of the preceding pages.

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Conclusions and Recommendations

FROM THE
AIAA ASSESSMENT
SOLAR ENERGY FOR EARTH

Conclusions

(1) Technical feasibility has been demonstrated for a number of solar-powered energy systems designed to provide terrestrial heat, electric power, or both.

(2) Solar energy can begin to make significant contributions to the nation's energy supply sometime in the period 1985-2000. Its present economic disadvantage as compared with alternative energy sources can be reduced or eliminated altogether if (a) a vigorous program of federal research and development support is provided, (b) the implementation of pilot-plant, demonstration, and prototype solar-powered plants is actively promoted, and (c) the prices of fossil fuels remain high or fluctuate unpredictably and nuclear power costs continue to rise.

(3) Identifiable environmental and sociological impacts of solar energy systems are far less severe than those associated with fossil-fueled and nuclear fission-powered systems. In particular, solar-powered systems do not deplete natural energy sources.

(4) In contrast to fossil-fueled and nuclear-fission sources, most solar energy systems depend critically on the availability of either energy storage facilities or supplementary power sources. This mismatch between available and demand power is not a problem for ocean thermal energy conversion powerplants or biomass energy and is of only minor concern for satellite solar power stations.

(5) Premature implementation of solar-powered energy systems without adequate research, technology, and development support, or demonstration efforts involving economically or operationally unsuitable components or systems, could lead to an undesirable "backlash" effect. Adequate R&D, pilot-plant, and demonstration projects should be accelerated but not bypassed.

(6) The first large-scale utilization of solar energy will be for hot-water heating, space heating, and to a somewhat lesser extent, space cooling. However, the other systems reviewed in this Assessment could make substantial contributions in the future. Specific conclusions regarding each of these systems are as follows:

(a) *Solar Heating and Cooling* will be used for supplementary energy in the new-building market particularly multiple-family dwellings. Life-cycle costs will become comparable with fossil fuels in the 1985 time period, and it is expected that 20% of all new buildings in the year 2000 will be equipped with supplementary solar power systems.

(b) *Solar-Thermal Electric Power* stations could be operational in selected locations by the late 1980's. The central-receiver system for intermediate-load operation is the preferred system for initial development. No technical breakthroughs are required, but extensive experience will be needed to reduce first-cost to competitive levels.

(c) *Photovoltaic Power's* technical feasibility is well established, but cost reductions by factors of at least 100 to 1,000 are needed to make it economically competitive. Ultimate prospects for such reductions are good, but economic feasibility could still be contingent upon other system component costs. Market capture will be limited solely by costs, since flexibility of scale, co-location with load, materials availability, and land use aspects are all favorable. Economic feasibility could be demonstrated as early as 1985.

(d) *Synchronous Satellite Solar Power* offers advantages over land-based solar energy systems in incident power level, energy storage needs, and thermal dissipation. Principal problem is cost, both of the enormous solar collectors and the transportation needed to get them into orbit. If the very large but necessary cost reductions can be achieved, this source could provide significant terrestrial power in the future, possibly in the first half of the 21st century.

(e) *Wind Power* can provide commercially feasible local powerplants with present technology. Principal problems are variability of the wind (need for storage or supplementary power) and the economics of large-scale utilization. Noncommercial prototype implementation on a limited scale could begin now, and demonstration of commercial feasibility in selected localities is possible as early as 1980.

(f) *Ocean Thermal Energy Conversion* appears to be technically feasible, with the closed-cycle concept the preferred option. Energy costs could be competitive with those of fossil fuels or nuclear power, and there is a major prospect for co-location with energy-intensive manufacturing plants; e.g., ammonia, hydrogen, aluminum, and magnesium. It is conceivable that ocean thermal plants could provide a significant contribution (e.g., 4% to perhaps as much as 10%) to U.S. power needs by the year 2000.

(g) *Fuel Production* (*Biomass Energy*) is commercially feasible to a limited extent today, using urban, farm, and forest-product wastes as fuel. Prospects for full-scale "energy plantations" depend primarily on fuel growing and processing costs and land use/transportation, but they could begin to look attractive by the year 2000.

All *the approaches discussed should be supported by an R&D and systems analysis effort.*

Recommendations

(1) Unless and until there is clear evidence that one or another of the various approaches to solar energy utilization should be emphasized in lieu of others, *all* the approaches discussed in this Assessment, including energy storage requirements where needed, should be supported by an aggressive, continuing long-term *research, development,* and *systems analysis* effort. Specific implementation plans for the various approaches are detailed in Chapters 5 through 11.

(2) Pilot-plant and demonstration projects should be implemented only in accordance with a time-phased integrated plan for the overall expansion of solar energy into the economy, setting up funding priorities and scheduling of the various approaches, since they are all competing to a substantial degree for the same market.

(3) Demonstration plants should be constructed and operations initiated in each of the proposed approaches only after technology readiness has been clearly established. Premature implementation can be counterproductive, as indicated in Conclusion (5) above.

(4) Mechanisms should be sought to encourage the early implementation and eventual mass production of solar-powered energy systems because of their great potential benefits in the conservation of natural resources and the reduction of environmental impact. Such mechanisms could include (a) tax credits or other economic incentives, (b) taxation or other burdens ("disincentives") on new alternative resource-depleting or polluting systems, (c) direct federal grants or other subsidies, if they can be justified on a broad basis, and (d) the use of comparative economic analyses which take into account all energy debits and credits (e.g., construction requirements and total-energy utilization) and include the actual costs of environmental, social, and international trade impacts.

(5) Collection of basic data needed to implement the various systems should be initiated immediately; e.g., on insolation (see Chapter 4), on wind characteristics (see Chapter 9), on ocean characteristics at certain sites (see Chapter 10), and on biomass properties (see Chapter 11).

Summary

FROM THE AIAA ASSESSMENT
SOLAR ENERGY FOR EARTH

This Assessment addresses seven classes of solar-powered systems capable of generating energy for terrestrial consumption. Each of these is considered in terms of current and projected technology, economics, environmental and social impacts, problems of interfacing with existing energy systems, market capture potential, and, where possible, comparisons with alternative approaches. Data and technology needs and recommended implementation plans are also identified.

The solar energy resource available to all seven system classes is called *insolation*, the incident solar radiation flux. Its average value just outside the Earth's atmosphere, called the *solar constant*, is 1.35 kilowatts per square meter (kW/m^2) or 125 watts per square foot (W/ft^2). Most of this energy is in the visible-light spectrum. Some of it (of the order of 30%, on the average), is absorbed, reflected, or diffused in the atmosphere by atmospheric gases (carbon dioxide and ozone), dust particles, and water vapor, including clouds. The insolation varies with geographical location, the season, the altitude, and the time of day. The average incident energy on a horizontal surface in one day can range, for example, from 1.1 kilowatt-hours per square meter (kWh/m^2), an average flux of 46 W/m^2, in Seattle in January, to approximately 9 kWh/m^2 (375 W/m^2) in the Mojave Desert in July.

Diffused (scattered) sunlight can range from 20% of the total ground insolation on clear days to 90% on cloudy days. Hence flat-plate absorbers and photovoltaic arrays which can utilize scattered light energy in addition to direct sunlight are subject to less variability in power output than are the direct-sunlight absorbers, which must focus direct rays in order to operate. Long-term variations in average annual insolation can be as high as 15%, with events such as volcano eruptions causing even larger long-term changes. The oceans, which both accept diffuse radiation and provide a natural thermal storage system, are affected least of all by variations in insolation.

Because performance appraisals and economic appraisals of solar energy devices can be no more accurate than the insolation data upon which they are based, the acquisition of insolation data should be given high priority.

Solar Heating and Cooling. The technology for the low-temperature flat-plate type of solar-energy collector needed for hot-water heating, space heating, and space cooling (including solar-augmented heat pumps) is well known. Installation of prototype systems in residences, office buildings, and building groups is under way in many parts of the country. The principal barrier to widespread use is the still-high system first cost, about half of which is chargeable to the collectors themselves. Also, supplementary energy sources are needed for nights and periods of low insolation, since it is economically impractical for solar energy, even with energy storage capability, to provide all heating and cooling needs.

Life-cycle costs are not competitive with existing systems now, but will be competitive by 1985 or sooner, depending on the rate of fuel price escalation. The speculative nature of future prices for fossil fuels and nuclear power, as in all solar-powered systems, is a key factor in market-capture projections. Also, the high first-cost of solar-powered systems, despite potentially attractive life-cycle costs, is detrimental to market capture for commercial buildings or developments. Other potential barriers can be incompatibility with zoning and building codes, possible concern about architectural esthetics, and as-yet unknown repair and maintenance costs. Structural and esthetic difficulties associated with the installation of solar energy systems on existing buildings tend to make costs excessive.

Despite these problems, it is almost certain that the first large-scale market for solar energy will be for hot-water heating, space heating, and, to a somewhat more limited extent, space cooling of new buildings, particularly multiple-family dwellings. Market capture projections (based on 1973 estimates of future fossil-fuel prices) range from about 1% to 2.5% of all energy consumed in the year 2000, but this percentage could be considerably larger if fuel price escalation is excessive. Competitiveness of solar energy in the heating and cooling market can be further enhanced by federally-financed proof-of-concept experiments, use in government buildings, economic incentives, and continued federal support of research and development.

Solar-Thermal Electric Power. Solar-thermal conversion systems collect solar radiation, converting it first to thermal energy and then to electric power. When they also supply heat for industrial processes or space heating, they are designated "total energy" systems. Solar-thermal conversion can be used in large central station powerplants (greater than 100 megawatts [MW]) or in smaller units (10 MW or less) located at the load site. When tied into a major power grid they can provide base load, intermediate load, or peaking power.

There are two basic types of solar-thermal systems: the central receiver and the distributed collector. In the central receiver system sunlight is reflected by many individual heliostats (mirrors) to a central tower where it is absorbed and converted to electricity by conventional methods. In distributed systems, the sunlight is absorbed by many individual absorbers, each having its own solar collector, and the thermal energy is then transferred by a fluid (such as water) to a central point for conversion to electric power. The energy is transported optically to a central point in the first case and hydraulically in the second. Because central receiver systems can obtain higher working fluid temperatures (550 - 800 K, or 530-980 F), they are more efficient for electric power generation and appear at present to provide the best economic approach in central-station (large) sizes. The relatively inefficient but potentially less expensive flat-plate collectors may be best suited for small-size units; e.g., for multiple residences or small shopping centers.

Solar-thermal electric power systems require either some form of energy storage, to accommodate mismatches between insolation availability and load demand, or full-time availability of standby power, such as an existing utility grid or auxiliary fossil-fueled generators. For storage, thermal energy appears to be the most practical, but costs increase rapidly with storage capacity. Hence there is a tradeoff between storage capacity and the availability of supplementary power for use when insolation outage periods exceed storage capacity.

Preliminary studies have identified the intermediate-load central receiver system as the preferred demonstration plant. It would have a collector (heliostat field) area of 1 square kilometer (km^2), about 250 acres, per 100 MW of rated plant capacity, 6 hours of thermal energy storage, and a projected busbar energy cost of 25-30 mills/kWh (1973 dollars). Although all elements of such a plant are within the capability of existing technology, extensive development will be required to yield low capital equipment and construction costs. Because of the size, capital costs, and construction time of solar thermal powerplants, as well as the need to explore alternative design approaches, no significant market penetration of solar-thermal electric power appears possible before the late 1980's.

Photovoltaic Power. Photovoltaic conversion of solar radiation directly to electric power can occur in a thin layer of appropriate material. Silicon, because of its great abundance, high conversion efficiency (10-15%), and advanced state of development appears at present to be the best photovoltaic conversion material, although there are other materials having special characteristics which may make them commercially attractive.

A basic advantage of photovoltaic power systems is their flexibility in size. The exposed surface area of photovoltaic converter arrays can range from less than one square meter to many square kilometers, making them much less sensitive to the economies of scale that force conventional fossil and nuclear powerplants and solar thermal systems to become very large. Since photovoltaic arrays can thus be co-located with their loads, thereby possibly avoiding much of the capital cost and power losses of power distribution equipment, they could be used for single family residences, commercial or public buildings, or industrial plants, as well as central station powerplants.

The technical feasibility of photovoltaic solar energy conversion has been well established. Photovoltaic "solar cells" have powered most of the spacecraft launched by all nations. However, the systems designed for space use are too expensive for large-scale terrestrial power generation: they cost about $200 per peak watt, and even their terrestrial versions still cost about $20 per peak watt. Cost reductions by a factor of 100 to 1000 are needed before photovoltaic power can become commercially useful on a large scale. Research and development efforts are in progress toward this goal, and an ultimate photovoltaic converter cost of $.10/watt by 1985 or 1990 is a reasonable expectation.

In addition to the photovoltaic converters, photovoltaic power systems require a mounting structure for the converters, a power collection network, electrical regulation and control equipment, probably power conditioning equipment to convert dc to ac, energy storage equipment, and possibly concentrators and cooling systems for the converters. These components are all technologically feasible, but their costs loom large, and the economic feasibility for large scale photovoltaic power generation may depend upon achieving low costs for these other components in addition to low cost solar arrays. Other factors such as land use, environmental impact, and materials availability, as in other solar energy system concepts, do not appear to be limiting.

Synchronous Satellite Solar Power. A solar power satellite in orbit about the Earth 35,800 km (22,000 miles) above the equator would always remain above the same point on the Earth's surface. The satellite would generate electricity from sunlight, using either arrays of photovoltaic converters or a solar-thermal electric system to power microwave transmitters. These transmitters would beam microwave power to a line-of-sight receiving station on Earth where special receiving antennas (rectennas) would convert it directly to dc power. If photovoltaic arrays were used, a receiving station net output of 5000 MWe would require a total satellite mass of 20 million kg

(22,000 tons), a satellite solar array of 45 square kilometers (17 square miles), a satellite microwave transmitting antenna 1 km in diameter, and a ground station receiving antenna 7.4 km (4.5 miles) in diameter. If space-rated solar array costs can be reduced by a factor of about 1,000 from today's costs of $200/watt, and a new, second-generation space transportation system were available which could deliver payloads at a cost of about one fortieth that projected for the present shuttle, the total system costs would be $1,000-3,000/kWe (1973 dollars). Projections using advanced solar thermal power systems with the satellite are similar.

The principal benefits of the satellite solar power station are (a) it receives up to 15 times as much sunlight as the same collector area on the Earth's surface, since it is never obstructed by the Earth's atmosphere (clouds), (b) it minimizes environmental impact on the Earth's surface, and (c) it requires 70 minutes or less of storage or back-up power (the maximum shadowing of the satellite by the Earth, which occurs at the equinoxes). Testing and studies to date have demonstrated the technical feasibility of the microwave transmission system. Despite the enormity of this concept, the potential payoff from its success warrants continued investigation of the critical technological and economic factors. Assuming development success in the great reductions in cost identified above, solar power stations could contribute significantly to energy availability on Earth in the future, possibly during the first half of the 21st century.

> *The first large-scale market for solar energy will be for hot water and space heating and cooling.*

Wind Power. Windmills have been an important source of power for centuries. They have been used by the millions since the middle ages to grind grain, pump water and saw lumber. More recent efforts to use windmills to generate electricity demonstrated some degree of technical success at power levels as high as 1.25 MWe, but were not competitive with the low cost and full-time availability of fossil fuel-generated electric power. As a result, wind power system development has been dormant for the last 10-20 years.

Winds are generated by the Earth's rotation and solar heating, which is strongly affected by clouds, nightfall, and terrain. Wind speed, turbulence, gusting, and direction also vary considerably with height and terrain. Additional wind data are needed to establish design conditions for wind power systems.

A wind power system consists of a rotor, a rotor direction controller, a transmission, an electrical generator, an ac frequency controller, a support tower, and either an energy storage device or equipment for tying into a utility power grid. Technical feasibility for wind power systems is well established, but there has been little experience with plant sizes over 10 kW, and much attention is needed to improve costs, reliability, and service life over those of past systems. Energy storage requirements are a function of wind power reliability (since winds are seldom steady, and extended calm periods can occur) and the availability and cost of supplemental power. These are relatively untreated aspects of wind energy systems and need more exploration.

Wind energy development in the United States is supported principally by federal programs, although many individuals and small groups are active in limited projects. System studies are needed to define the most economically competitive applications for wind energy.

Wind power systems have extremely favorable environmental attributes, can be located immediately adjacent to their load customers, and can be deployed rapidly by mass production techniques. Because of these advantages, and if the demonstration programs are successful, commerical feasibility of wind powerplants could be established within five years. Because this is a very short time in the context of electrical utility planning, power companies throughout the United States have been invited to participate actively in the testing of the experimental wind plants.

Ocean Thermal Energy Conversion. In 1929-30 the first crude ocean thermal energy conversion plant, using the temperature difference between the sun-heated ocean surface and the deeper cold layer, was built and operated. Its turbine generated 22 kWe by using vacuum evaporated sea water directly in an open Rankine cycle. Subsequent work has shown that a closed Rankine cycle using working fluids such as ammonia, with warm sea water heating the boiler and cold sea water cooling the condenser, is probably more efficient and less costly.

Much of the ocean area within 10° latitude of the equator has a surface temperature 20 C (36 F) or more above the temperature at a depth of about 1000 meters. These conditions are suitable for powerplant operation. However, since most of this energy would be consumed at a considerable distance from its source, coastal locations are also receiving attention.

A satellite solar power station would receive up to 15 times as much sunlight as on the surface.

A number of conceptual powerplant designs have been proposed and are now undergoing engineering evaluation. Extensive tradeoff studies are required to determine the most cost-effective configurations. Turbine design appears to be relatively straightforward because of low tip speeds, pressures, temperatures, and temperature variations. The boiler and condenser heat exchangers will be the largest and costliest components of the powerplant. They pose the greatest design challenge, not only because of their size, but also because of (a) the high heat-transfer efficiency required by the small temperature differences available, (b) the problem of biofouling from organisms that flourish in the warm water and (c) the possibility of high corrosion rates in the sea water. The pipe to bring cold water up from below the surface also represents a design challenge because of its size and the large drag forces on it from external currents. Except for the turbine, no direct experience exists for the major powerplant components. Considering related expense with marine and other systems, however, all problems recognized to date seem to be capable of engineering solution, but design studies and experiments are needed to verify the solutions and their economic feasibility. A major advantage of ocean thermal energy conversion is the availability of virtually infinite storage capability— the oceans themselves.

Economic comparisons with fossil fuel and nuclear powerplants indicate that ocean thermal plants can cost as much as $900-1700/kWe and still supply cost-competitive electric energy, based on current prices for fossil fuels and nuclear powerplant capital costs in the $500-1,000/kWe range. Since several economic performance estimates for ocean thermal plants are within this range, a strong development program for them appears appropriate.

A significant alternative to bringing electric power to shore is the moving of energy-intensive manufacturing processes out to sea. Among the products that could be manufactured at the ocean-based plant are ammonia (e.g., for fertilizers), liquid hydrogen (high grade fuel), aluminum, and magnesium.

Commercially feasible ocean-thermal powerplants could relieve the social, environmental and political problems of developing more power generating capacity on land. There are political ramifications of siting a plant outside the 12-mile limit, since such sitings would need protection if not the political sanction of other nations. There are also environmental concerns related to offshore siting, but these are not likely to be as important as the onshore problems of alternative power-generation systems.

Fuel Production (Biomass Energy). The natural process of photosynthesis, which provides combustible (and renewable) plant matter for energy production, supplied over 95% of the world's fuel up to the year 1800. Although it is not practical, efficient, or economic for today's densely populated industrial nations to depend on these resources, it is possible to develop biomass fuels to an extent which can substantially reduce dependence on fossil fuels.

There are three potentially valuable sources for biomass fuels: urban wastes, farm wastes, and dedicated fuel crops or "energy plantations." Urban wastes have been studied extensively as a potential fuel source, utilizing anaerobic (non-oxygenating) bacteriological reduction of wastes to fuel-rich gases and commercially useful recycled products. No new technology is required; economics alone dictates the potential viability of these processes. Farm wastes, too, are currently being utilized as a source for both fuel-gas and recycled commerical products, and this practice will undoubtedly be expanded as competing fuels and alternative waste-disposal options become more costly.

The exploitation of dedicated fuel plantations is not yet economically viable, although land-based perennials such as eucalypti and marine cultures such as giant sea kelp offer much promise as future biomass fuels. Key elements in exploiting such systems are improving photosynthetic efficiency and the collection/harvesting processes. The most logical scenario for implementation of this energy resource is one in which conversion of urban, farm, and forest-produced wastes to fuels would initially replace perhaps 10% of current fossil fuel consumption. As the national waste-generation patterns change to reflect future increased energy costs, energy plantations utilizing either trees or giant sea kelp could become economical.

The technology for pilot-plant operation of dedicated energy plantations is available now. However, systems analyses and experimental studies are needed to evaluate the economic and ecological feasibility of large-scale biomass conversion. A search for potential new classes of high-yield vegetation for fuel sources could improve profitability, as well as development of efficient economic collection capabilities for both biomass wastes and dedicated energy crops. ■